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SYMPOSIUM ON DETECTION OF SUBSURFACE CAVITIES 12-15 JULY 1977.(U)
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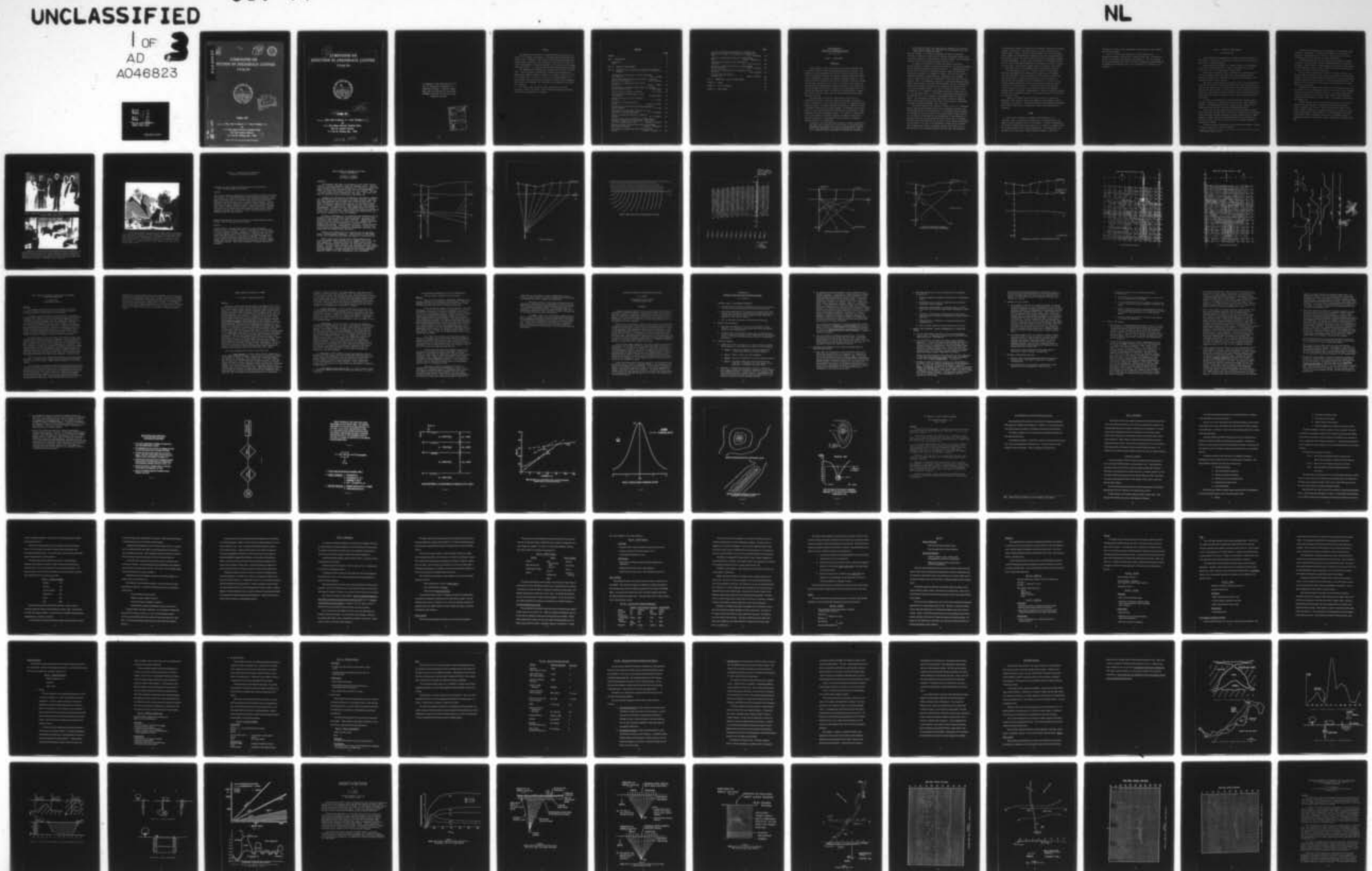

SYMPOSIUM ON
TECTION OF SUBSURFACE CAVITIES

12-15 July 1977

October 1977

Sponsored by **Office, Chief of Engineers, U. S. Army, Washington, D. C.**
and
U. S. Army Engineer Waterways Experiment Station
Soils and Pavements Laboratory
P. O. Box 631, Vicksburg, Miss. 39180

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SYMPOSIUM ON DETECTION OF SUBSURFACE CAVITIES

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PREFACE

The Symposium on Detection of Subsurface Cavities was held 12-15 July 1977 at Vicksburg, Mississippi. The Symposium was sponsored by the Office, Chief of Engineers (OCE), under the Civil Works Investigational Studies (CWIS), Materials - Rock Research Program (Work Unit 31150, entitled "Improvement of Geophysical Methods"), and the Soils and Pavements Laboratory (S&PL), U. S. Army Engineer Waterways Experiment Station (WES).

The Symposium was organized and coordinated by Mr. Dwain K. Butler, S&PL. Other individuals instrumental in planning and organizing the Symposium were Messrs. Robert F. Ballard, Jr., Joseph R. Curro, Jr., and Don C. Banks, S&PL. Mr. Paul R. Fisher is the Program Manager of the Rock Research Program and was the OCE point of contact for the Symposium. This report which documents the proceedings of the Symposium was edited by Mr. Butler.

Mr. James P. Sale was Chief, S&PL, during this period, and COL John L. Cannon, CE, and Mr. Fred R. Brown were Director and Technical Director, respectively, of the WES.

CONTENTS

THE SYMPOSIUM ON
DETECTION OF SUBSURFACE CAVITIES
12-15 July 1977

PART I: INTRODUCTION

Background

Almost weekly it seems that reports of problems encountered with construction sites on solution susceptible bedrock are surfacing. The problems are being encountered not only with new construction but with existing structures and range from reservoir leakage through dam foundations to catastrophic collapse of roadways, buildings, dams, etc. Although the Corps of Engineers has had and is having its share of problems in such areas, the Corps can not claim to be unique in this regard, as problems are being encountered by numerous agencies of the Federal and State Governments and by private contractors and consultants both in this country and around the world. The problem is basically that of subsurface cavities and many complicated and interrelated geotechnical manifestations of them.

The Symposium on Detection of Subsurface Cavities, held in Vicksburg, Mississippi, 12-15 July 1977, was an attempt to define the scope of problem and to review the state-of-the-art in geophysical cavity detection methods. Although originally envisioned as a meeting of Corps of Engineers personnel with invited speakers, the Symposium grew considerably in size with representatives attending from universities, private companies, and other government agencies. In an effort to direct attention to the problem of subsurface cavities in general, the following definition was given on questionnaires sent to possible attendees to appraise interest in the Symposium:

> Definition: The term "subsurface cavity" is broadly interpreted to mean any void or pocket (air or fluid filled or filled with some secondary geologic material) in soil or rock which may or may not have surface expression. Cavities may be geological in origin (i.e., formed by solution processes in limestone and dolomites or

by tectonic activity in any type rock) or man-made (such as buried pipes, tunnels, mines, etc.) and may vary in dimensions from a few centimeters to hundreds of meters.

Thus the problem is considered to encompass all forms of subsurface cavities, in addition to those found in solution susceptible bedrock such as in Karst regions, including those of military interest such as intrusion tunnels, missile silos, explosion-induced cavities, etc.

For proposed construction in areas with potential subsurface cavity problems, two courses of action are possible: (a) avoid the problem, and (b) accept the problem and develop solutions. If subsurface cavities are found to be a threat to existing structures, again two courses of action can be defined: (a) abandon the project, and (b) "live with the problem" and attempt remedial measures. Regardless of the ultimate course of action, the scope of the problem at a given site must first be defined. Due to the fundamental limitations of geological mapping, aerial remote sensing methods, and direct contact methods, the use of geophysical methods are required to help define the problem and thus provide input to the decision making process. In the site selection process for new construction, it is imperative that geophysicists have an early part in the site evaluation aspects. Geophysical reconnaissance methods can play an important role in the avoidance or abandonment decisions (items (a) above). Also geophysical detailing applications can play an important role in defining and delineating the scope of the problem for developing solutions and remedial measures (items (b) above).

The keynote address by Mr. William E. Davies of the U. S. Geological Survey, case history presentations by Corps of Engineers personnel, and the presentation by Mr. Richard Hopkins of the Tennessee Valley Authority were intended to define the scope of the problem faced by those involved in site selection and evaluation and investigation of the foundations of existing structures in areas where subsurface cavities may be a problem (particularly those areas which may strictly or even loosely be classified as Karst areas). Not only is the percentage of land area in the United States underlain by solution susceptible bedrock quite large; but, as more and more of the preferred building sites are used, the probability

of encountering foundation problems due to subsurface cavities will increase greatly. The problem is only rarely that of a single, large cavity at shallow depth. Instead, the more common problem is one of cavity systems: highly complex and interconnected, varying in size, and often extending to great depths. Hence, the task of detecting cavities by geophysical methods is quite challenging. In many cases the detection of individual cavities will not only be practically impossible but meaningless in terms of utility. For these cases, the preferred approach may be to delineate cavity zones or cavity-prone zones in the foundation with the geophysical methods.

The presentations by Mr. D. K. Butler of the U. S. Army Engineer Waterways Experiment Station (WES) and Mr. Richard Benson of Technos, Inc., were intended to give an overview of cavity detection methods and their applicability. Technical presentations on specific detection methods were then intended to give an introduction to a variety of geophysical methods applicable to the cavity detection problem and provide a review of the state-of-the-art. The specific methods include high resolution seismic reflection, other seismic methods, electromagnetic methods (radar), resistivity, microgravimetry. Extensive discussion periods following each presentation allowed a free exchange of ideas and clarification of major points.

Finally, an informal "round table-type" discussion climaxed the Symposium. This allowed a direct interchange of ideas between a panel of experts and the audience. Outstanding questions and problems were addressed, and a look to future needs in geophysical research and development was presented.

Scope

This report is intended to document the proceedings of the Symposium. Due to time and fiscal constraints, the presenters were not asked to present complete copies of their papers. Instead, the presenters were asked to prepare detailed abstracts and, if possible, to supply copies of the illustrations used in their presentations. The abstracts are reproduced, for the most part, without editorial changes. Outlines or

transcripts of three of the presentations were available in more complete form and are included.

Part II of this report consists of a press release on the Symposium, prepared by the WES Public Affairs Office, and is an excellent account of the purpose and content of the Symposium. Part III contains the Symposium Abstracts, and Part IV presents a Summary and Recommendations. The Agenda, a Bibliography, and a List of Attendees are presented in the Appendices.

PART II: SYMPOSIUM PRESS RELEASE

by Barbara Cain*

"Five hundred dead in parking lot collapse." Disaster headlines of the future? It just could be, according to William E. Davies, geologist with the U. S. Geological Survey.

Davies made the statement in his keynote address at the Symposium on Detection of Subsurface Cavities held in Vicksburg this past week (12-15 July 1977) at the Magnolia Best Western Motel.

Sponsored by the Office, Chief of Engineers, in Washington and the Soils and Pavements Laboratory (S&PL), WES, the Symposium attracted geologists, geophysicists, geotechnical engineers, administrators, and planners from all over the country.

The cavities under study are subsurface voids in the earth caused by solution, the process of chemical weathering that causes rock material to pass into the liquid state. Cavities are not easily detected, and unfortunately, they have occurred in the foundations of even preferred construction sites. Since many of the more desirable sites have already been used, future construction may be necessary on sites where subsurface cavities are likely.

To avoid the catastrophe of possible structural collapse, proper foundation study must be conducted to locate and treat these underground caverns. The Symposium was directed to geoscientists, engineers, and managers who must deal with this type of engineering problem.

Taking turns at the lectern during the week were experts from the WES, District and Division offices of the Corps of Engineers, the Tennessee Valley Authority, Southwest Research Institute, Colorado School of Mines, Lawrence Livermore Laboratory, Texas A&M University, the University of Missouri at Rolla, and even a professor from the Campagnie Generalde de Geophysique in France.

Methods of cavity detection fall into three main categories: remote sensing, ground-surface, and direct contact.

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* WES Public Affairs Office.

Remote sensing methods have the advantage of covering large areas quickly and economically. Although these methods are not capable of locating or delineating specific cavities, they can be used to select problem areas for more intensive study by other methods.

Ground-surface methods include, among others, seismic, electrical resistivity, self potential, acoustic subbottom profiling, and gravity surveying. These methods of surface geophysical exploration vary greatly in their ability to reveal specific cavities, but some have potential as valuable subsurface cavity location tools.

Direct contact methods, the third class of cavity detection, are the only means of definitely establishing the existence of cavities. These methods, using borings and excavation, may be used to prove out potential cavities indicated by remote sensing or surface geophysical methods. The high cost of drilling and the time involved limit application of these methods for exploration.

Emphasis of the Symposium was placed on the presentation and review of state-of-the-art in geophysical cavity detection as the most promising method of locating these subsurface caverns. Both formal presentations, including engineering case histories, and informal "round table-type" discussions were employed to develop topics of instruments, methodology, and capabilities.

Several dignitaries were on hand Tuesday morning (12 July 1977) to kickoff the 4-day Symposium. Attendees were welcomed by COL John L. Cannon, Commander and Director of WES, followed by Paul Fisher of the Office, Chief of Engineers, who explained the interest and needs of the Corps of Engineers in cavity detection. The keynote address was given by William E. Davies, a geologist with the U. S. Geological Survey. Symposium coordinators were Dwain K. Butler and Robert F. Ballard, S&PL, WES.

Left to right above: J. P. Sale, Chief, S&PL, COL Cannon, Davies, Fisher, Butler, and Ballard.

Geologists, geophysicists, geotechnical engineers, scientists, and administrators from all over the United States, as well as representatives from Canada, Puerto Rico, and the Dominican Republic, convened in Vicksburg last week (12-15 July 1977) for a series of lectures and panel discussions on methods of subsurface cavity detection.

A native of Vicksburg, Dr. Charles Kolb (right), who is a geologist of note in the professional community, attended the Symposium and enjoyed "shop talk" with a colleague, Dr. R. R. Unterberger of Texas A&M University, during a break. On Wednesday afternoon (13 July 1977), he conducted attendees on a historical-geological tour of Vicksburg National Military Park. Dr. Kolb, who holds a Ph.D. degree in geology, retired from the WES in 1973.

PART III: ABSTRACTS OF THE SYMPOSIUM ON DETECTION OF SUBSURFACE CAVITIES

Gathright Dam, Case History of Seismic Wavefront Investigations - John C. Bowman, Middle East Division

Abstract

During final foundation explorations for Gathright Dam, borings encountered open cavities in the dam abutment below the proposed pool elevation. Since near vertical dip jointing was common, there was heated discussion whether narrow solutioned joints or actual large open cavities were involved. Additional core borings did little to confirm either viewpoint. Seismic wavefront surveys were conducted to expand the borehole information with some success, however, they were unable to resolve the dispute. Downhole TV was able to confirm severe solutioning in the abutment and exploratory adits were used to further refine the abutments karstic nature. Special foundation treatment was required to control leakage through the left abutment because of these cavities.

Radford Army Ammunition Depot, Case History of Seismic Wavefront Investigations - Carl S. Anderson, Norfolk District

Abstract

Seismic Wavefront techniques were employed to locate subsurface discontinuities at a proposed site for a large ammunition manufacturing facility at Radford, Virginia. Subsurface conditions at the site consist of soluble limestone and dolomite formations. Numerous sink holes are evident and some are active. The results of the wavefront studies and their correlation with core boring data are presented. Problems with setting charges and several methods employed are also discussed. Double spreads were shot from several drill holes by coupling two twelve channel seismographs together. The results and method of coupling the units is discussed.

CASE HISTORY OF MERAMEC PARK LAKE CAVITY DETECTION

Gregory L. Hempen
St. Louis District

Abstract

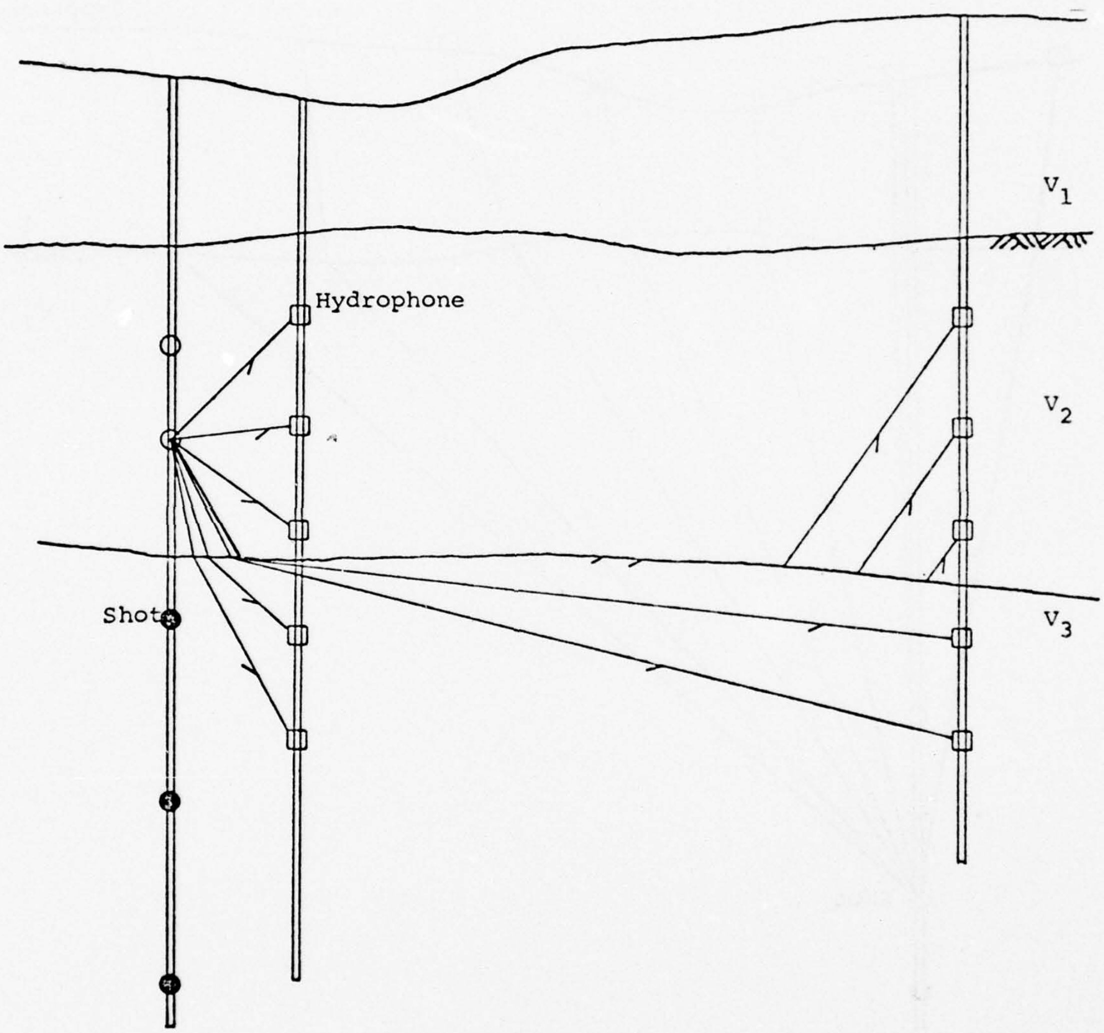
The Meramec Park Lake is situated in the Ozark Plateau region of Central Missouri along the Meramec River. The controling rock formations are Cambrian and Ordovician dolomites. These dolomites are solutioned and have cave development. Sinks are only occasionally present in the uplands. The dam is rock-filled with an impervious clay core. The rock fill will be quarried from the emergency spillway cut.

Seismic and resistivity methods were utilized to explore for detrimental rock conditions including solution openings and other passages which might make grouting difficult. Uphole shooting was used extensively in the uplands and abutments; crosshole shooting was deployed in the valley where the near surface ground water table supported wave passage to hydrophones. Seismic coverage overlapped along the entire grout curtain and beyond. Both Wenner and Bristow resistivity arrays were utilized to determine practical application for particular purposes in this environment.

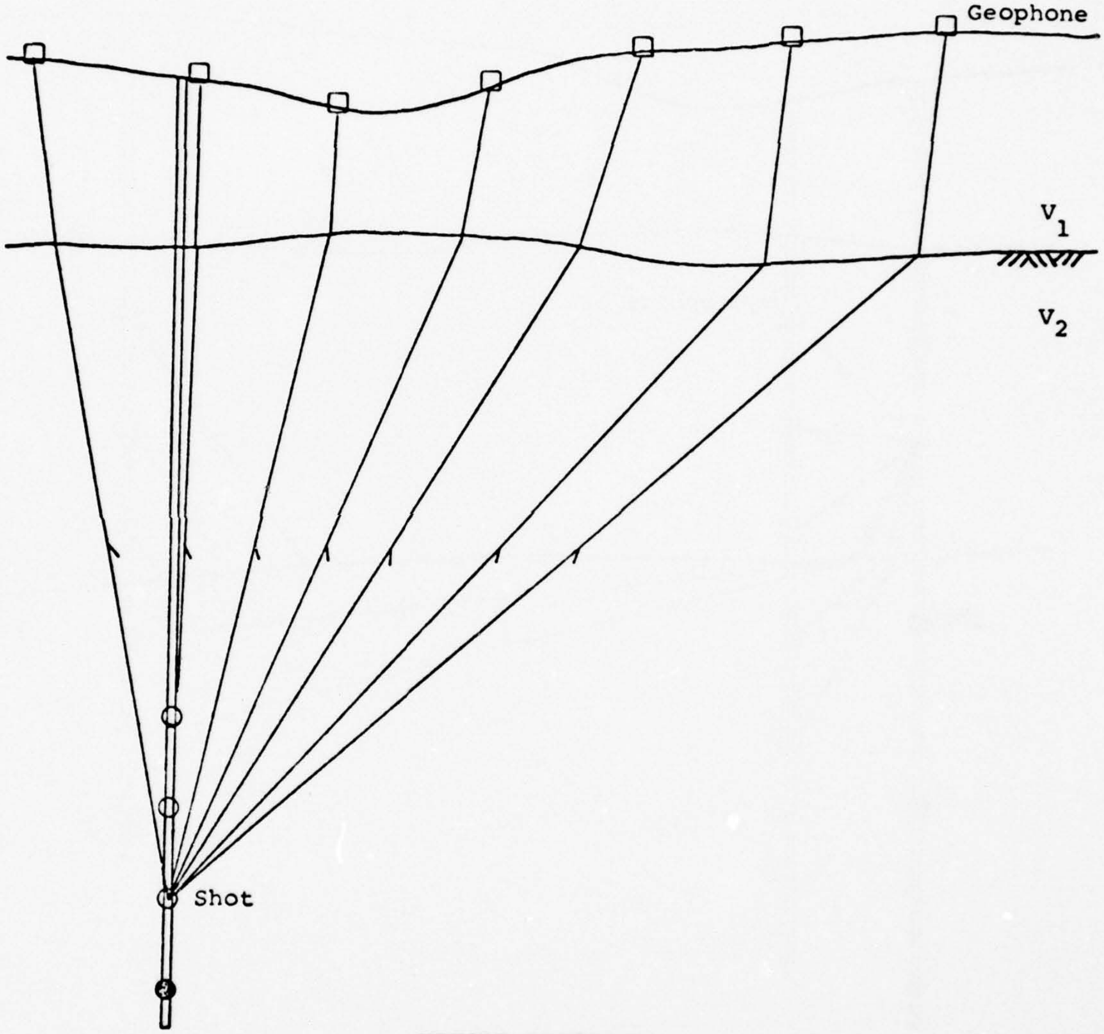
Analysis techniques of the shooting was predominately by seismic refraction methods, minimum-distance velocity interpretation, and Meissner wavefront diagrams. Advantages of in-hole seismic shooting at this site are: simple equipment, shock source and array deployment, and availability of computer processing. Disadvantages include: arrays limited to borehole coverage; topographic and bedrock inaccuracies, which should be checked; deceiving subsurface coverage; and resolution of anomaly cause and size.

Resistivity exploration was limited, but in selected cases verified known anomalies. Power source of the resistivity unit restricted severely the depth of investigation.

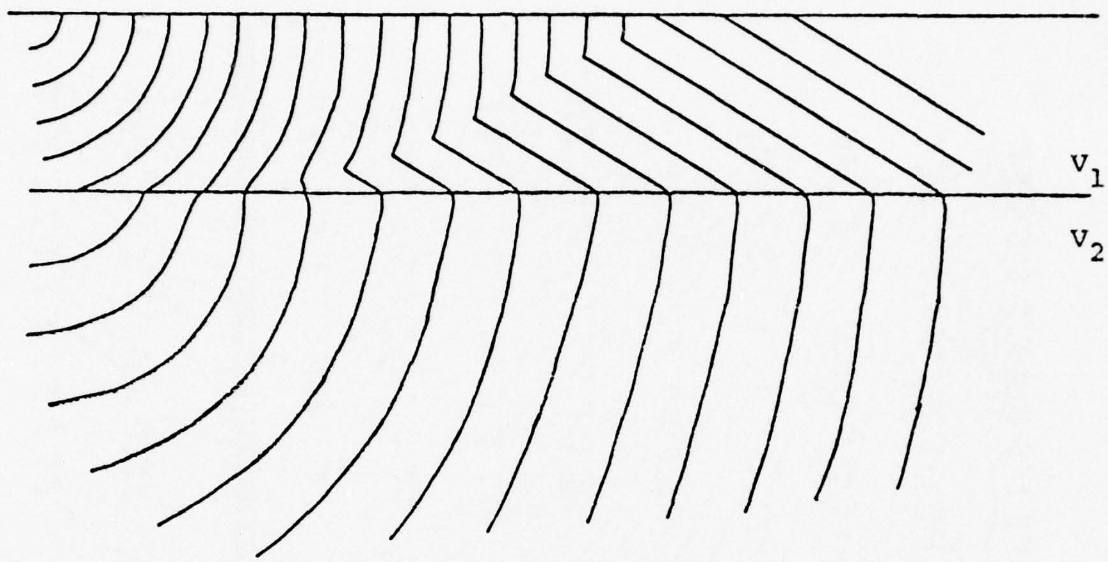
Known caves were analyzed with uphole shooting to evaluate method effectiveness and to compare with grout curtain anomalies. Anomalies along the grout curtain were drilled following their discovery to determine severity and extent. Seismic inhole analysis was compared with RQD values, borehole pressure testing, test grouting results, and known cave development. Seismic methods at this site predicted anomalies which have been determined to be groutable.



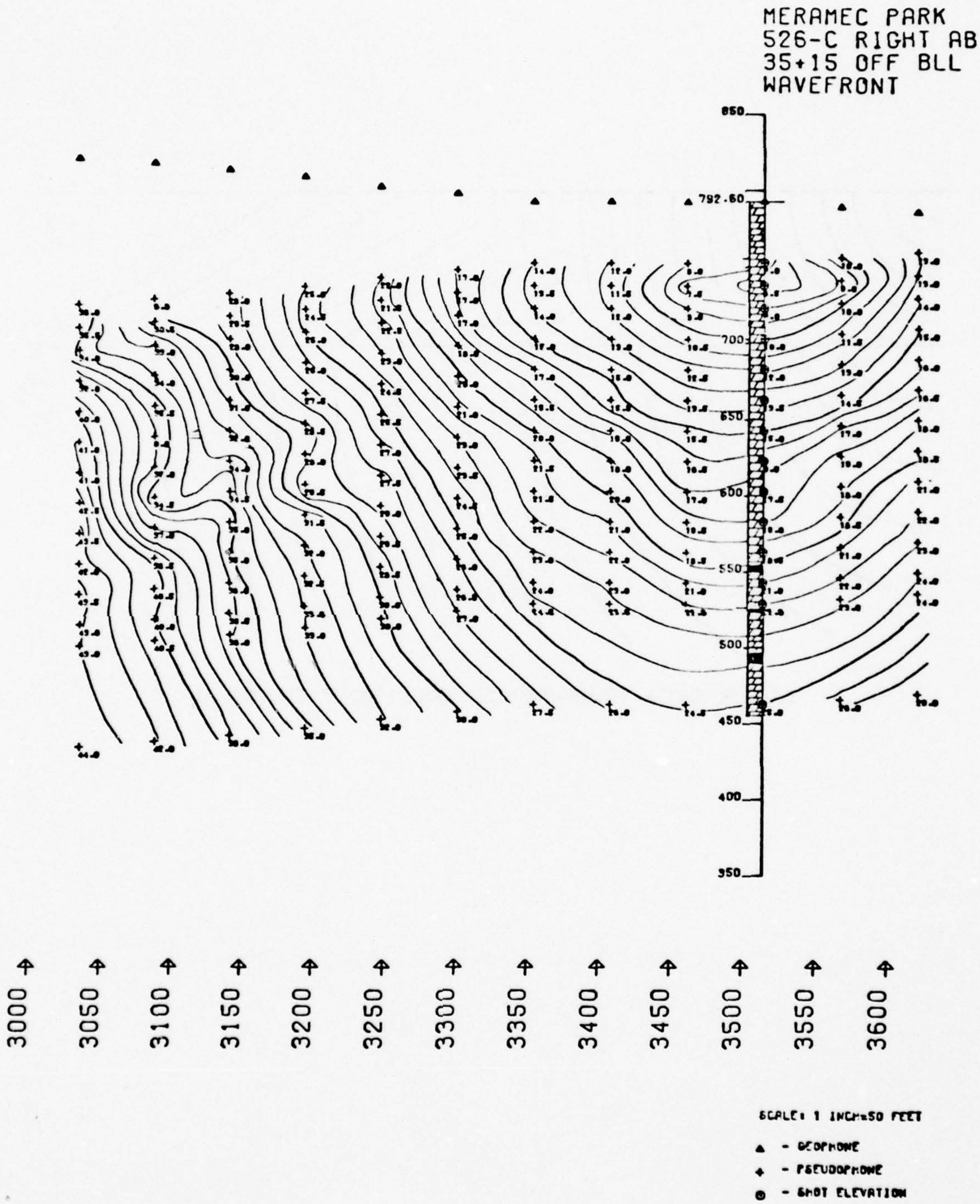
CROSSHOLE SHOOTING

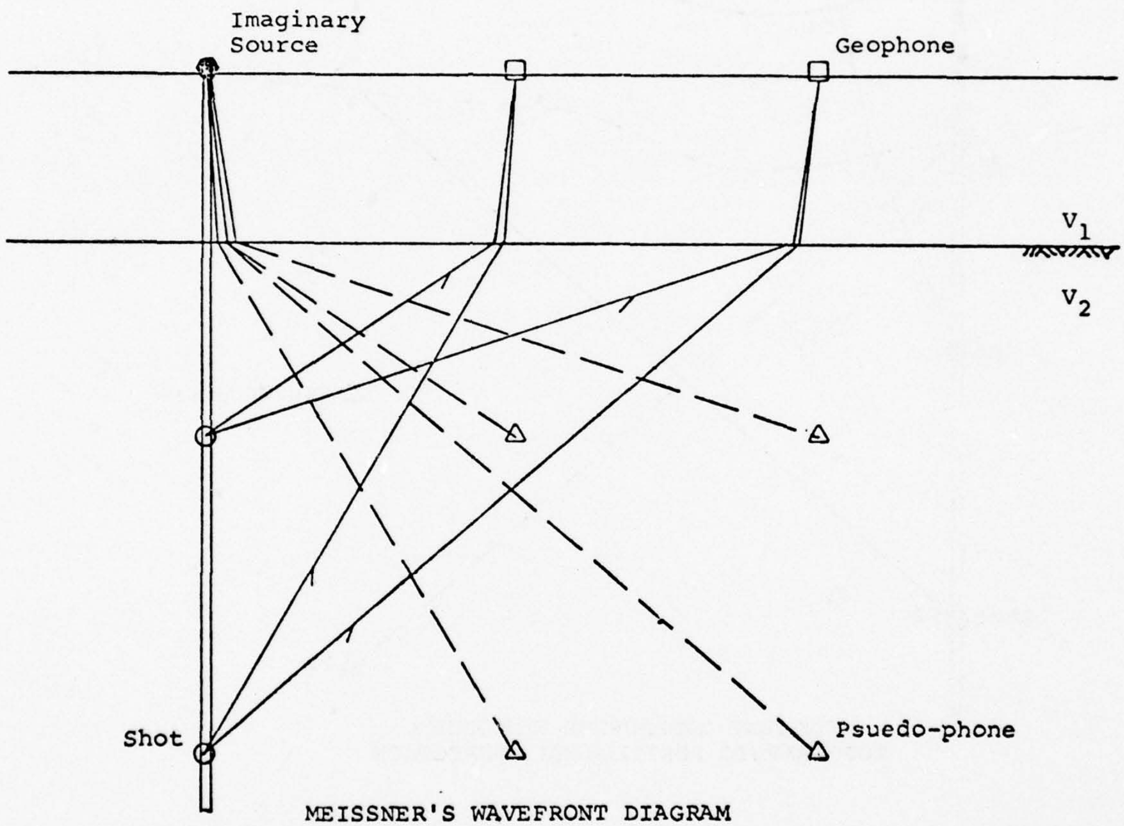


UPHOLE SHOOTING

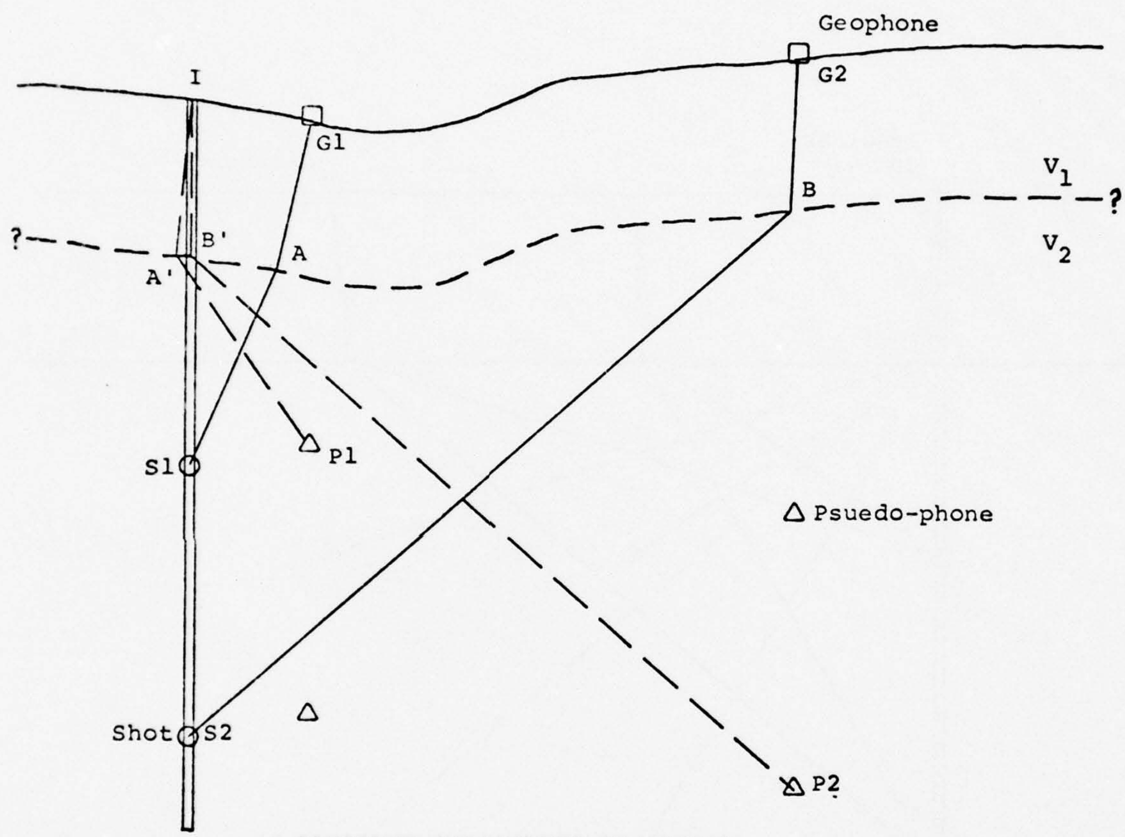


LAYER OVER HALF-SPACE WAVEFRONT DIAGRAM

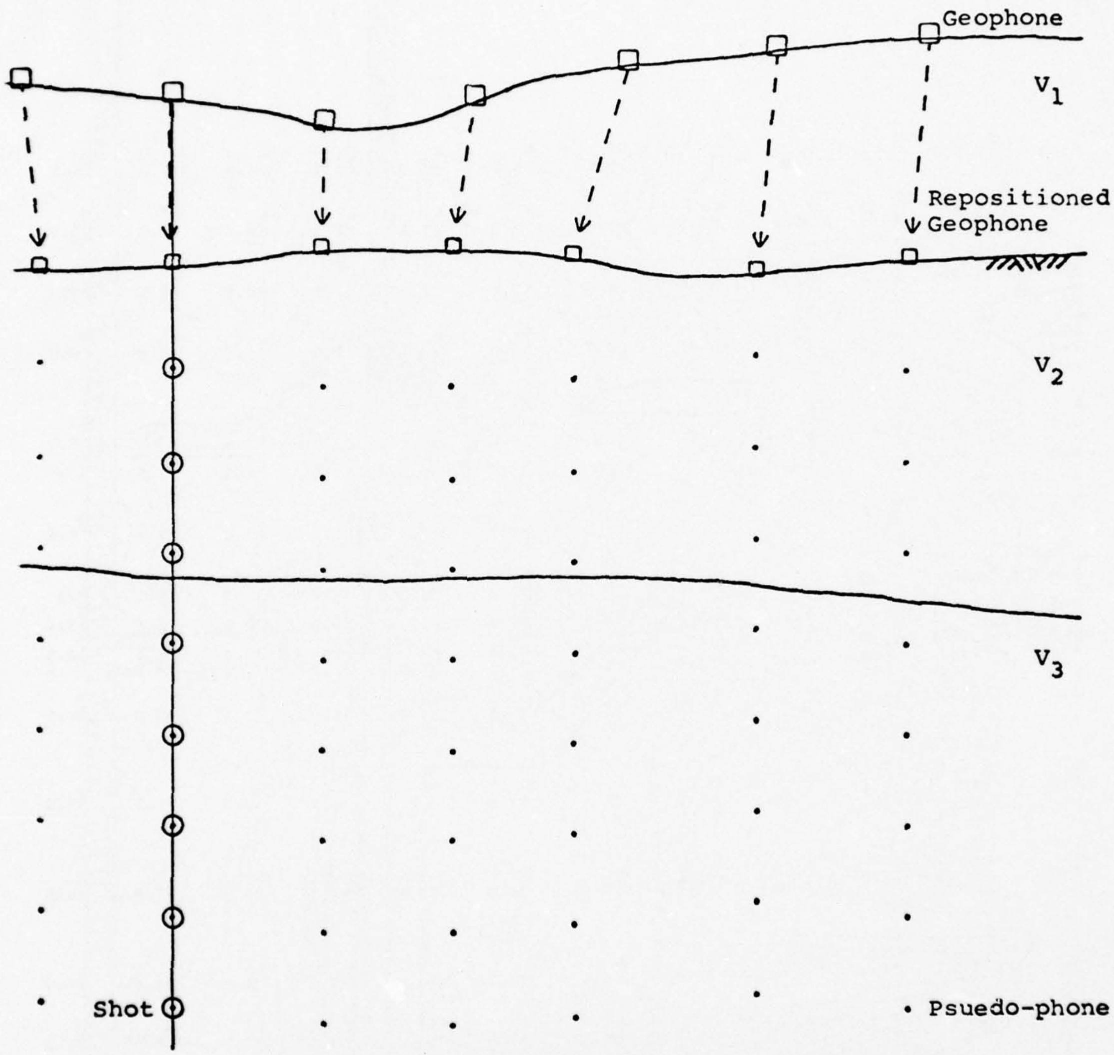

MERAMEC PARK
526-C RIGHT AB
35+15 OFF BLL
WAVEFRONT
SCALE: 1 INCH=50 FEET
▲ - GEOPHONE
✦ - PSEUDOPHONE
◉ - SHOT ELEVATION



MEISSNER'S WAVEFRONT DIAGRAM

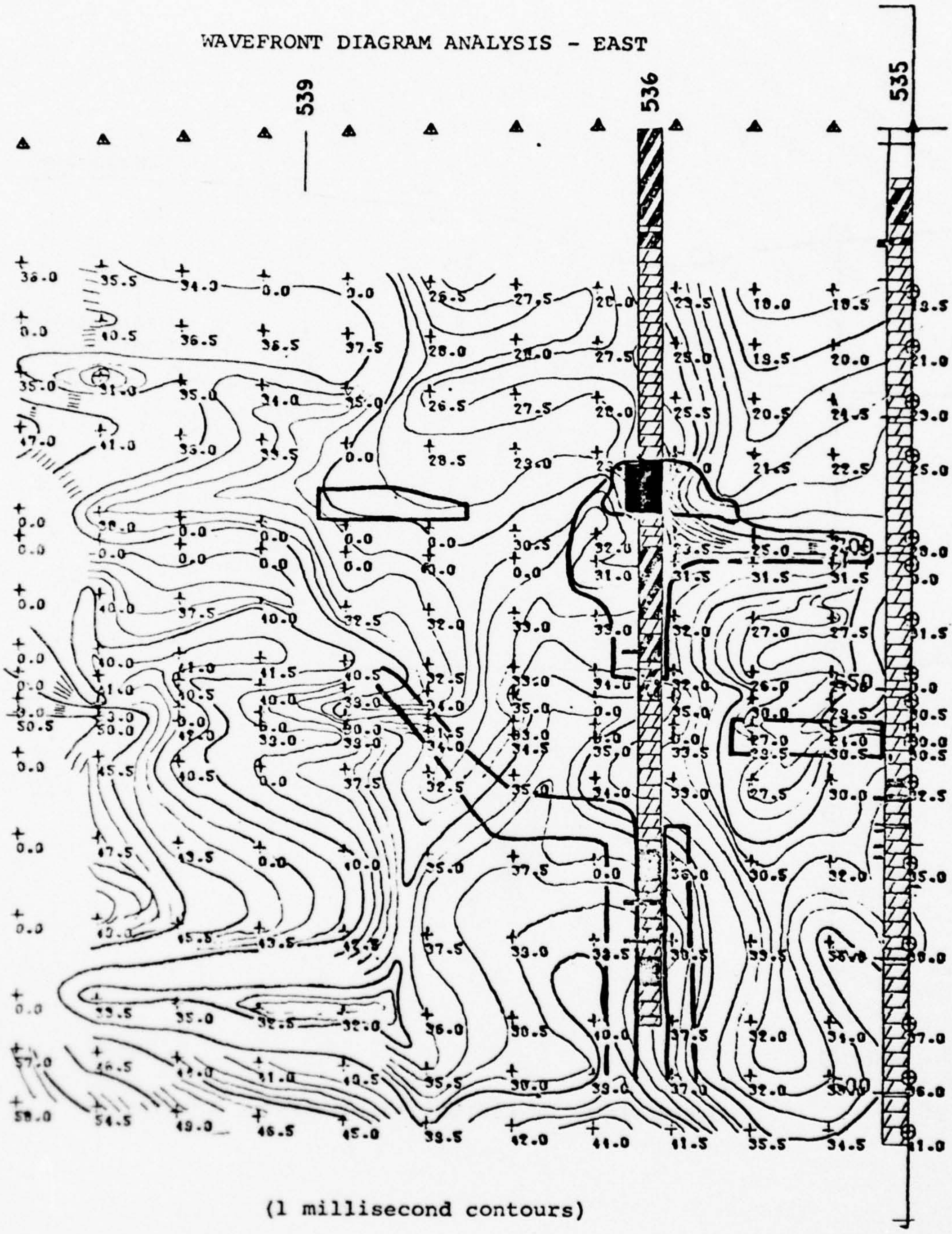


CONSTANT OVERBURDEN THICKNESS
TOPOGRAPHIC POSITIONING CORRECTION



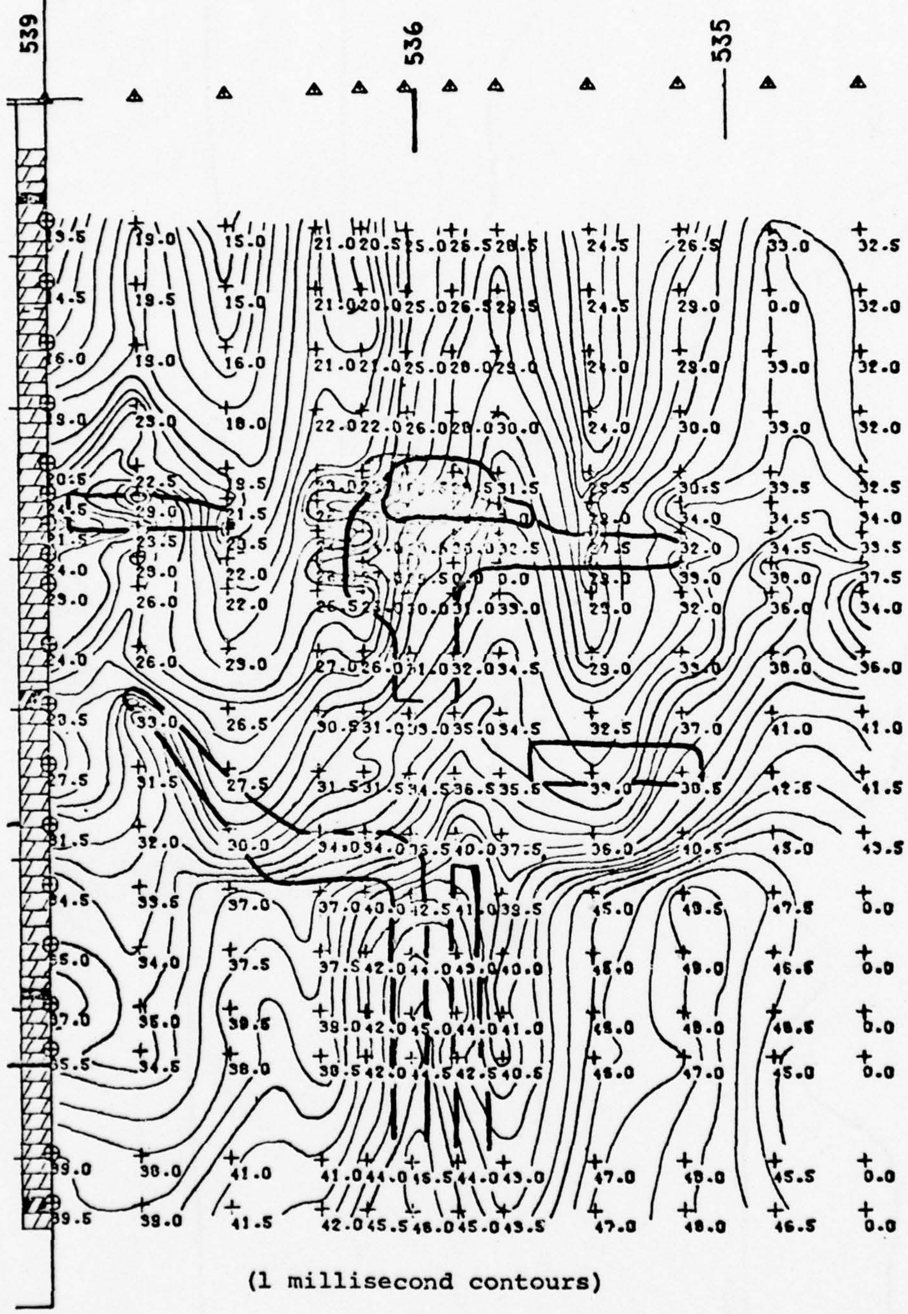
OVERBURDEN "STRIPPING" FOR WAVEFRONT ANALYSIS

WAVEFRONT DIAGRAM ANALYSIS - EAST



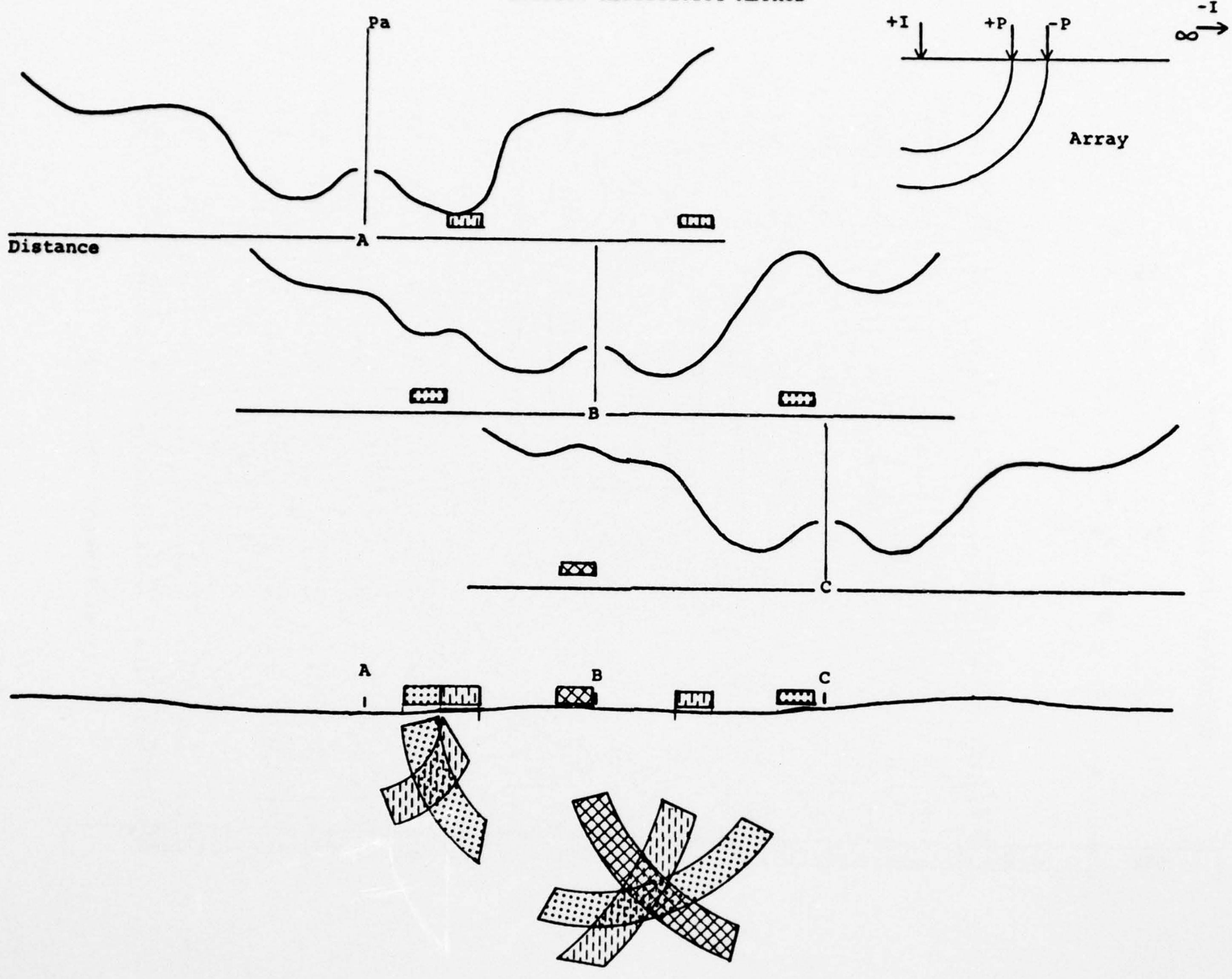
(1 millisecond contours)

WAVEFRONT DIAGRAM ANALYSIS - WEST



(1 millisecond contours)

BRISTOW RESISTIVITY METHOD



CASE HISTORIES, PROBLEMS OF BURIED KARST AND CAVERNS
FLORIDA AND PUERTO RICO

C. Fred Dreves
Jacksonville District

Abstract

The Jacksonville District's major construction activities in Florida are located in areas almost totally underlain by soluble limestone varying in age from recent to late Eocene.

The younger limestones occur in southern Florida. The rock is highly solution riddled, sometimes cavernous and often interbedded with or underlain by clean sand or other unconsolidated materials. The occurrence, thickness, hardness, and other engineering characteristics of the limestones change rapidly over short distances. Some have described southern Florida as a mass of mortar looking for a place to set. Closely spaced core borings often fail to reveal buried cavities encountered during construction. Refraction Seismograph Surveys have failed to provide usable records because of the interbedded nature of the rock (limestone underlain by less dense material such as sand). Seepage control and dewatering structure excavations in the solution riddled or cavernous limestone is a major design consideration.

The older limestones occur in central and northern Florida. Extensive cavern systems, buried Karst topography, and large springs such as Silver Springs at Ocala, Florida, are present. The limestones are part of a major aquifer which is the primary source of potable water for much of Florida. The entire area is pockmarked with sink holes. Primary topographic features are controlled by solution activity and underground erosion along solution channels. Sinkhole lineations and spring locations appear to be controlled by faulting. Sinkhole formation is currently taking place with the most active periods during dry seasons. Many sinks are inactive and have been for years, but on occasions and for unexplained reasons, new sinks develop adjacent to inactive ones.

The water filled cavern systems are difficult to trace using known techniques. Seepage control, foundation design, dewatering provisions, and protection of the aquifer require detailed knowledge of the cavern systems.

The occurrence of subsurface cavities and other natural forces are causing major foundation problems at the San Juan National Historic Sites in the old city of San Juan, Puerto Rico. The Jacksonville District is currently performing field investigations for foundation remedial treatment at these sites. The historic sites are located on an elongated whaleback-shaped ridge composed of a series of cemented sand dunes resting upon a limestone reef foundation which may in turn be underlain by unconsolidated clean sand. Each cemented dune in the series is

separated from the underlying one by a more permeable relic soil mantel. The dunes are transected by near vertical joints. Surface water entering these joints seep downward to the relic soil mantels and then flows down the dip of the mantels to be discharged near the sea. The surface water moving along the soil mantels causes cavities parallel to the bedding both by erosion and chemical decomposition. As the weak zones form, large blocks of the cemented dunes at the cliff face are free to move. Locations of the cavities are essential for foundation remedial treatment design.

TUNNEL DETECTION PROBLEMS IN VIETNAM

E. E. Addor, Terrain Analyst, WES

Abstract

During the years of the Vietnam conflict, the ground forces of the United States and its allies were hampered by the enemy's use of extensive, well concealed tunnel networks. Obviously, means of detecting the presence of a tunnel complex and determining its extent would have provided an important tactical advantage for the friendly forces. The conceptual approaches to the problem of tunnel detection were focused upon the hypothesis that the presence of a tunnel in an area would create certain detectable anomalies in the environment of that area. During March and April, 1967, an interdisciplinary terrain analysis team from the Waterways Experiment Station (WES) went to South Vietnam to gather quantitative measurements of various environmental factors in and around tunnel complexes, for guidance in establishing the suitability or the sensitivity requirements of various experimental or hypothetical sensor systems. The data were compiled and published as WES Misc. Paper 4-919, "Environmental Characteristics of Tunnels in South Vietnam, by this author, dated August 1967 (reprinted Aug 1968). The report consists mostly of a straightforward compilation of the collected data, with descriptions of the instruments and procedures employed, and discussions of problems encountered. The data are presented in 40 tables and 39 plates with descriptive notes, all extensively indexed and cross-referenced. Except for directing attention to certain points which may be of interest to those engaged in sensor development, there is but minimal attempt to interpret the data in terms of specific sensor requirements. March and April are at the peak of the dry season in the area studied, and any search of these data for potentially significant sensor signatures, or possible sources thereof, must be made with this bias in mind.

The factors measured and included in the report are:

a. Tunnel geometry. For one tunnel, interior features and ground surface features pertinent to both detection and denial techniques are described in detail on a short segment, and the general pattern of the complex over an extensive area is indicated. For another complex, data are given for interior detail and for general pattern. These two tunnels are similar in many structural details, but they differ significantly in the size of the passageways, in the intricacies of the (known) network, and in the frequency and size of identifiable storage rooms, sleeping bays, and other activities rooms. These differences are thought to be related to function; the complex with smaller passageways, more intricate network, and fewer rooms is believed to be a tactical tunnel, while the other is believed to be designed primarily for logistical

purposes. Salient features of the tunnel geometry, with respect to production of significant sensor signatures, are: the absence of surface soil disturbance during construction; the small size and irregular location of vent holes; exits (in the complexes observed) being located close under dense shrubbery and carefully concealed with camouflaged trapdoors; frequent and irregular changes in direction of the passageways; the presence of interior trap doors closing and concealing offsets in direction and elevation; and variability in the dimensions and horizontal and vertical placement of passageways and various utility chambers.

b. Surface composition. Tunnels observed during this study were in the following soil types--gray podzolic (Cu Chi and Quang Ngai), red-yellow podzolic (Cu Chi), reddish-brown laterite (Long Phuoc), and earthy-red latosols (Pleiku). Nearly all measured soil strength values were in excess of 4.5 kg/cm^2 as measured by a pocket penetrometer. Seismic-wave velocity and attenuation curves were obtained for the Cu Chi and Long Phuoc tunnel areas, and electrical conductivity curves are shown for soils of Cu Chi and Pleiku.

c. Microclimate. The data include (1) soil surface temperature profiles variously oriented to the tunnel, and temperature profiles inside the tunnel, at tunnel openings, and above tunnel openings; (2) relative humidity in and around a tunnel opening; and (3) air flow through the interior of the tunnel. A cursory examination of these data indicates that no significant difference existed between soil temperatures over the tunnel and away from the tunnel, or if present, the difference was obscured by background variation. The soil temperature in general was lowest at about 0700 hr. At any given place within the tunnel, the temperature was nearly constant during the period of measurement, varying from about 79 F at the coolest place measured (tunnel under woods) to about 82 F (tunnel under open field); at an opening there was a sharp and rapid fluctuation of relative humidity which appeared to be accompanied by a corresponding fluctuation of temperature; and though the interior temperature and relative humidity were quite high, at about 79-82 F and greater than 80%, the air inside the tunnels was nonetheless fresh and acceptable.

d. Vegetation. Both vegetation structure and taxonomic data are presented. To the extent of the observations made during this study, it is not evident that vegetation in any way influences the construction of tunnels, though it may influence their location to the extent that maximum advantage is made of taller vegetation (woods, plantations, etc.) for concealment of exits where possible. Also, neither is it evident that the presence of a tunnel alters the appearance of vegetation standing above it.

e. Visual appearance and reflectivity. At a scale of about 1:1000, no evidence of tunnels could be seen on camouflage detection or infrared photography.

TVA PHILOSOPHY AND METHODOLOGY FOR SITE INVESTIGATION

Richard Hopkins, Tennessee Valley Authority

Abstract

Most of the TVA region is underlain by limestone, which presents problems in site foundation investigations. Each site, depending upon the type of structure to be built, must be independently evaluated in regard to foundation conditions.

There are two main points in TVA's foundation exploration philosophy. First is the role that the geologist plays in using all available information in order to coordiante with the geophysicist as to the type and possible location of solution features or other adverse foundation conditions. Thus the geologist and geophysicist determine the exploration program and coordinate their proposal with the design engineer. The second point is the zone investigation approach. Our experience has shown that most solution problems are caused by a series of small joint-controlled and/or bedding plane features, rather than large single cavities. It is almost impossible as well as uneconomical to try to locate each solution feature. The zone investigation approach, which acknowledges the possibility for treatment of these small features after opening the foundation, has caused no major redesign of a TVA structure, except in the case of Normandy Dam, where a cutoff trench had to be added.

TVA, turning its attention from coal-fired plants and dams to nuclear power, which would require intensive foundation evaluations, combined with the rising cost of core drilling, was forced to search for other methods to obtain engineering data. TVA began percussion drilling rather than core drilling to complete exploration holes for geophysical logging, at a savings of one-third the cost per foot and one-tenth the time.

TVA maintains two geophysical borehole logging trucks and has proven the effectiveness of the borehole technique for foundation investigations by logging more than 3,000 holes. Geophysical sondes used for engineering foundation investigations are mainly sonic, 3-radii caliper, and density. Other sondes (resistance, gamma, temperature, neutron) are used for special problems such as stratigraphic correlation. It is necessary to use more than one type log to make an accurate interpretation, depending upon the information sought.

Phase I of a plant site evaluation consists of a comprehensive regional geologic investigation. Phase II, a localized site evaluation program is formulated, which consists of in-depth review of geologic literature and a site visit. Detailed geologic mapping, remote sensing, tectonic studies, refraction survey for top of rock, and in some instances gravity and resistivity studies for weathering phenomena, comprise the

third stage of investigation. Then recommendations based on results of phases I and II, determine limited percussion drilling and geophysical borehole logging to be performed.

Continuous cross-hole logging has a definite place in exploration, though more work on its capability needs to be done. High-resolution reflection investigations are also being planned for a rapid reconnaissance studies. High-resolution data recording is at the state-of-the-art, but data acquisition (field techniques) and data reduction (computer programs), although also at the state-of-the-art, need to be updated.

In summary, within TVA, the geologist, geophysicist and design engineer work together to evaluate foundation conditions. Their respective contributions must be sought in the early stages of investigation and coordinated throughout the life of the project. Future TVA investigations will continue to include borehole, cross-hole, and reflection techniques, and a continued search will be made for other methods to satisfy engineering data requirements.

GEOPHYSICS VERSUS THE CAVITY DETECTION PROBLEM

D. K. Butler

Waterways Experiment Station
Vicksburg, Mississippi

Abstract

Geophysical methods applicable to the cavity detection problem can be categorized as passive or active. Similarly the methods can be classed as aerial, surface, or subsurface in their mode of application. The geophysical methods are powerful and versatile but should not be blindly applied to a given site investigation. The role of geophysics in a site investigation should be an integral part of the overall program and not considered in an ad hoc fashion.

Field use of the geophysical methods can be classed as reconnaissance or detailing applications. Many times the methods and general field procedures will be the same for the two types of application with the amount of data processing and interpretive effort being the difference. Often the reconnaissance applications may involve only a qualitative interpretation, but in general it is desired to cover large surface areas in a minimum of time. Detailing applications would be motivated by a need for more definitive subsurface data in limited areas, such as determining size or extent of cavities indicated by other means (reconnaissance geophysical survey, boring program, surface expression, etc.) or foundation investigations for relatively small, critical structures.

The key links between geophysical field data collection and geologic interpretation of the data are data processing and model postulation or calculation. It is important to realize the roles each of these play in the interpretation process. For example, in many of the modern high-resolution methods, data processing is of primary importance and the project geologist or engineer may not have the "instant access" to the interpreted data he desires. Models of the subsurface geology are indispensible in arriving at the final geologic interpretation, but the user as well as the geophysicist should always be aware of the fact that the models are not necessarily unique.

Geophysical methods which have been applied to the cavity detection problem are gravity, seismic, electrical, magnetic, electromagnetic, and subsurface counterparts to the preceding. It is important in the application of any of these methods to be aware of the type of geophysical anomaly a subsurface cavity would represent. The cavity problem is extremely diverse and challenging; and there is a great need for new detection techniques and improved application, resolution, and interpretation of existing techniques.

PRESENTATION

GEOPHYSICS VERSUS THE CAVITY DETECTION PROBLEM

D. K. Butler

I. IDENTITY CRISIS IN ENGINEERING GEOPHYSICS

A. Potential users shy away from geophysics because of the association with solid-earth geophysics and petroleum exploration.

B. Practicing geophysicists view engineering geophysics with some distaste and if forced to become involved occasionally will not perform the work with the same diligence as more tradational geophysics, hence quality suffers.

C. Work is frequently performed by inexperienced personnel.

II. BRIGHT SPOTS ON HORIZON

A. Many users are beginning to realize that geophysics offers valuable, cost effective reconnaissance and detailing possibilities in site investigations.

B. Geophysicists are beginning to realize that the problems presented in engineering geophysics are interesting and challenging. Also many schools are offering courses oriented to engineering geophysics.

III. GEOPHYSICS ARSENAL

A. Geophysical methods applicable to the cavity detection problem and in general can be categorized as passive or active methods.

1. Passive - Gravitational magnetic (natural radioactivity, thermal, self-potential, telluric current)

2. Active - Seismic, electrical, electromagnetic

3. Passive - Measures perturbations of natural potential fields

4. Active - Introduces energy into earth and measures perturbations or changes to the input energy or perturbations to an induced potential field

B. Similarly, the methods may be aerial, surface or subsurface. Most surface methods have subsurface counterparts in the familiar well-logging techniques. In addition there are innovative subsurface methods such as crosshole seismic, electromagnetic, and resistivity methods and surface-subsurface methods such as the Meissner Wavefront technique and uphole methods.

C. All geophysical exploration methods can be classed as remote sensing techniques. In addition to standard geophysical remote sensing techniques, a subdiscipline of the geosciences called Remote Sensing has experienced a meteoric rise in recent years. In general this consists of aerial photographic or satellite telemetered coverage of the surface in the form of black and white, color, false-color, infrared, radar, etc., imaging techniques. These methods are extremely valuable in even small-scale site investigations in that they enable us to recognize large-scale features such as general tectonic framework, drainage patterns, etc., which can have significant effect on site suitability even though they might be missed by standard site investigation reconnaissance techniques. Professor D. J. Belcher, formerly of Cornell University, has presented some classic examples of cases where sinkholes, subsurface drainage, and subsurface cavities were missed in standard site investigations but which could have been predicted by proper application and interpretation of aerial photographs.

Also, recent work sponsored by the Alabama Department of Highways has shown that lineaments or linear features indicative of joints, fractures or faults generally associated with openings in bedrock and vegetative stress or anamolous vigor which show up on aerial remote sensing plates can be diagnostic of impending sinkhole development.

D. Thus even though the geophysical methods which I am briefly discussing and will be covered more thoroughly in subsequent presentations are powerful and versatile, they should not be blindly applied to a given site investigation without a thorough consideration of Remote Sensing possibilities and study of geological evidence and available literature.

IV. FIELD USE OF THE METHODS CAN BE CLASSED AS RECONNAISSANCE OR DETAILING APPLICATIONS

A. Many times the reconnaissance applications may involve only a qualitative interpretation, but in general it is desired to cover large surface areas in a minimum of time. These would include aerial methods, (such as airborne magnetic surveying) some of the electrical resistivity methods and the equipotential mapping methods, and seismic methods such as surface refraction and fan shooting. Often it is the motive which leads to a reconnaissance application of a geophysical method such as the desire only to have general indications of subsurface anomalies (cavities) at the beginning of an investigation and not necessarily to know exact size or depth.

B. Detailing applications could be motivated by the following: (Vu graph #1)

1. Follow-up mapping of anomalies indicated on a reconnaissance survey.

2. Determining size or extent of anomalies such as cavities indicated by boring program.

3. Foundation investigations for relatively small, critical structures such as nuclear power plants, abutments for dams, etc.

4. Subsurface investigation of anomalies which have surface expression such as sinkholes, disappearing streams, vertical pipes, etc.

5. Investigations of foundations of existing structures for remedial action.

6. Areas of known subsurface mining operations in the past.

V. MODELS, DATA PROCESSING, GEOLOGIC INTERPRETATION OF GEOPHYSICAL RESULTS

A. The key links between field data collection and geological interpretation of geophysical results are data processing and model postulation. (Vu graph #2)

B. Data processing is the name of the game in modern applied geophysics. It can be as simple as hand-picking first arrival times from a seismic refraction record and producing time-distance plots or as complicated as wavlet processing of high resolution seismic reflection data. In any event, the user should not necessarily expect to have instant access to interpretated data in the field since the more complex processing algorithms require computer processing of the data.

Indeed after hearing some of the presentations in this symposium on high resolution methods you may be led to make a statement such as this by Richard Oldham (1906). (Vu graph #3)

C. Geophysical models of subsurface geology are indispensible in arriving at the final geologic interpretation of the geophysical data. (Vu graph #4) In dealing with models we speak of a direct or an inverse problem. For the direct problem, we postulate a model and then calculate results we would expect to observe from a geophysical investigation of the model. This is usually a simple and straight-forward procedure. The hypothetical model results can then be compared with field measurements to test the plausibility of the model.

The inverse problem involves deducing or calculating a model directly from the field measurements. This is more complicated and less straight-forward and the results are frequently not unique, i.e., more than one type of subsurface structure could account for the data.

D. Examples of use of models

1. As an example of the use of a geophysical model, we recently reviewed the results of a site investigation at an earth dam where the subsurface structure inferred from surface refraction surveys was grossly in "disagreement" with subsurface profiles developed from crosshole seismic tests. This crosshole profile is illustrated in the next Vu-graph (#5). Now, using this profile as a model consider the results of a hypothetical seismic refraction traverse with geophones at 25 ft spacings. (Vu-graph #6) The next illustration shows a time-distance plot of various arrivals, with the solid lines defining first arrivals. Note that not only is the low velocity layer missed but also the 1500 fps layer would not be detected. Thus when we observe only one velocity of 1150 fps on a 150-200 ft refraction line we have to say that it is <u>not</u> inconsistent with the crosshole profile model, since a traverse length of greater than 205 ft would be required to observe anything else.

2. As another example of the use of models, consider a sphere and a horizontal circular cylinder as two likely models of subsurface cavities. Surface gravity profiles over the anomalies are easily calculated and appear in the next Vu-graph (Vu-graph #7). The profiles are plotted in dimensionless form. Results such as these are useful in predicting optimum station spacings and minimum sizes and maximum depths of detectability.

   Also we can construct contour patterns which would be indicative of these anomalies. (Vu-graph #8).

E. Geologic interpretation and tests

1. Finally, after the data processing and model calculation and postulation, the product is some sort of geologic interpretation.

2. The ultimate test of the geologic interpretation of the geophysical site investigation is the drill bit.

3. Two questions come to mind regarding the geologic interpretation--

   a. How should we view the interpretation as a whole if we drill an anomaly and find nothing?

   b. If our interpretation shows no anomalies (cavities) can we safely assume there are no subsurface cavities at the site?

   c. These two questions relate to considerations of detectability thresholds and resolution and also the possibility of alternate interpretations, i.e., other possible models.

   d. These are questions with which it would be appropriate to confront the presenters.

VI. SCOPE OF THE PROBLEM

A. Well, enough of the high-sounding philosophy - what is the scope of problem we are considering from the detection point of view? We have heard details yesterday and this morning regarding the complexity we may encounter at typical sites, and in general, with my assessment of the state of the art in detection technology, I have to conclude that the problem is extremely diverse and challenging. There is a great need for new detection techniques or improved application, resolution, and interpretation of old techniques.

B. In many of the presentations to follow, experimental work has been done over known subsurface cavities with varying degrees of success, and this is certainly the way to start in the development of detection techniques. I'll concede the fact that, if a cavity is known to exist at a particular site, I or at least someone could probably conceive of a geophysical technique to deomonstrate its existence. But what of the general problem? Would you interpret the indicated "anomaly" as a cavity if you didn't know it existed prior to the tests? Also, many times in the literature and perhaps even in the talks to follow it is stated that the tests, which in most cases are in-line methods, should be conducted perpendicular to the major trends of the subsurface cavity system. Again, this is very presumptious! Richard Benson in the next talk will give an overview of cavity detection methods and his philosophy of how to attack the general problem at a site about which little is known. And in spite of our attention in this meeting to specific detection methods we need to always keep in mind that the ultimate goal is a general site investigation methodology in areas where cavities are known to be or may be a problem.

C. In general the impression I get from the literature is that if the cavities are very large, very shallow, or a fortiritous combination of the two we stand a good chance in detecting the cavities with standard field procedures. A good rule of thumb is that the depth can be no more than 1.5 - 2 times the "effective diameter," of the cavity. Thus we might expect to be able to locate a 15 m diameter cavity if less than 30 m depth to its center, or a 3 m diameter cavity if less than 6 m deep. But we might anticipate that a 50 cm diameter cavity at 1 m depth would probably not be the fortuitous combination I spoke of.

D. When I first heard of the cavity detection problem several years ago, my only previous experience with the subject was with a class project gravity survey over the Carlsbad Caverns. Beautiful results! So my first reaction to the posed problem was - give me a trusty Worden gravity meter and I'll find all the cavities you want. Obviously my experience was with an ideal situation, and the real world of cavities does not usually present the size anomaly represented by Carlsbad. Still the excellent density contrast of an air-filled cavity makes gravity surveying an attractive possibility; the air-filled cavity representing a negative gravity anomaly. The advent of microgravity meters with sensitivities of the order of 1 μ gal improve the prospects, and indeed Robert Neumann, who will be speaking on Thursday, is one of the pioneers of the application of microgravity meters to cavity detection. Also, application of the vertical gravity gradient method, which effectively samples an additional dimension than the standard survey method, has intriguing possibilities. This method has been applied quite successfully for the location of abandoned, ancient mine shafts in Poland (Vu graph #9). In fact, it is claimed that success has been so good that a drill rig will frequently follow the geophysical party in the field to drill indicated anomalies.

E. Seismic methods have been applied to cavity detection with quite varied degrees of success. Some investigators have observed time delays in refraction time-distance plots over known cavities while other investigators have seen completely negative results. The successes are probably examples of favorable combinations of cavity size, depth, traverse length, and geophone spacing. In general, <u>standard engineering</u> refraction and reflection surveys have not been and are not expected to be of much value generally in the detection of cavities. The frequency response of conventional geophones represents wevelengths in rock far larger than the small, localized targets represented by cavity systems. Recent use of high resolution seismic reflection techniques, modern data processing methods, and recognition of basic wave-cavity interaction mechanisms indicates, however, that seismic methods can play an important role in cavity detection. These recent results will be discussed further in todays session. Another seismic method which has been used with varying

degrees of success has been the wavefront method (Meissner). This method requires the use of boreholes which in many cases eliminate its use due to economic constraints or practicality considerations. Also these methods have been plagued by improper application and misinterpretation of results. Gus Franklin will discuss some of the pitfalls in Meissner Wavefront interpretation on Friday. The seismic fan shooting method has been used with some degree of success in Alabama; and the method appears to be a valuable reconnaissance tool.

F. Electrical resistivity methods are frequently applied to cavity detection problems and have been successful in many instances. The great value of the general technique is it great versatility; the same general field procedure and equipment can be used both in rapid reconnaissance or detailed mapping applications. The variety of possible electrode configurations give the method its flexibility. The absence of a number of papers devoted to electrical methods is not intended to reflect the importance in cavity detection programs but is merely due to the unavailability of individuals contacted. Resistivity work will be referred to however, in several of the presentations and particularly in Lou Fountain's paper on Thursday. Resistivity methods have been helpful in cavity detection even when all other methods have been of no value. In general, the air-filled cavity will represent a high-resistivity anomaly, while the fluid-filled or clay-filled cavity will represent a low-resistivity anomaly.

Electrical methods have been developed and applied extensively in the Soviety Union, and considerable success in cavity detection is claimed in the Upper Crimean Karst regions.

The Russians have also had success in using self-potential measurements to detect reservoir leakage paths - they call this the streaming potential method. In a slight variation they will determine equipotential maps of an area before <u>and</u> after dumping salt into the reservoir near suspected leakage sites - differences in the equipotential maps being diagonostic of the leakage paths.

G. The magnetic survey method is rapid and relatively inexpensive; however, for the detection of cavities in Karst regions (where we are most likely to have engineering problems) the method will not be of much value. An exception might be for <u>clay-filled cavities or sink-holes</u> in limestones and dolomites where the higher magnetic susceptibility of the clay would produce a magnetic high. This method has proven of value for the location of clay-filled sinks in the chalk in England. The method might also be of value for locating tunnels or mines in hard rock (igneous and metamorphics).

H. Electromagnetic methods are perhaps the newest and most unfamiliar of the techniques we will consider during the Symposium and I hope the presentations will serve to introduce us both to the methods and the possibilities. As instrumentation and our ability to interpret the data progress, I think that EM methods will emerge as some of the most useful geophysical tools for site investigations. This will primarily be due to the ability to sweep through wide frequency ranges.

I. Most of the methods discussed have borehole counterparts - borehole gravity meters, crosshole, and downhole seismic methods, crosshole electromagnetic, plus all of the standard well-logging methods. While the radius of investigation of most of the well-logging methods is quite small, they do extend the investigated zone several times over that examined by the borehole itself. In the case presented by William Baldwin yesterday afternoon, this increased zone of investigation was sufficient to detect cavities just missed by the borehole. Some of deep induction electrical tools may offer even better prospects for cavity detection although they would indicate depth but not necessarily distance or direction from the borehole.

MOTIVATIONS FOR GEOPHYSICAL DETAILING APPLICATIONS

1. FOLLOW-UP MAPPING OF ANOMALIES INDICATED ON A RECONNAISSANCE SURVEY.
2. DETERMINING SIZE OR EXTENT OF ANOMALIES SUCH AS CAVITIES INDICATED BY BORING PROGRAM.
3. FOUNDATION INVESTIGATIONS FOR RELATIVELY SMALL, CRITICAL STRUCTURES SUCH AS NUCLEAR POWER PLANTS, ABUTMENTS FOR DAMS, ETC.
4. SUBSURFACE INVESTIGATION OF ANOMALIES WHICH HAVE SURFACE EXPRESSION SUCH AS SINKHOLES, DISAPPEARING STREAMS, VERTICAL PIPES, ETC.
5. INVESTIGATIONS OF FOUNDATIONS OF EXISTING STRUCTURES FOR REMEDIAL ACTION.
6. AREAS OF KNOWN SUBSURFACE MINING OPERATIONS IN THE PAST.

Figure 1

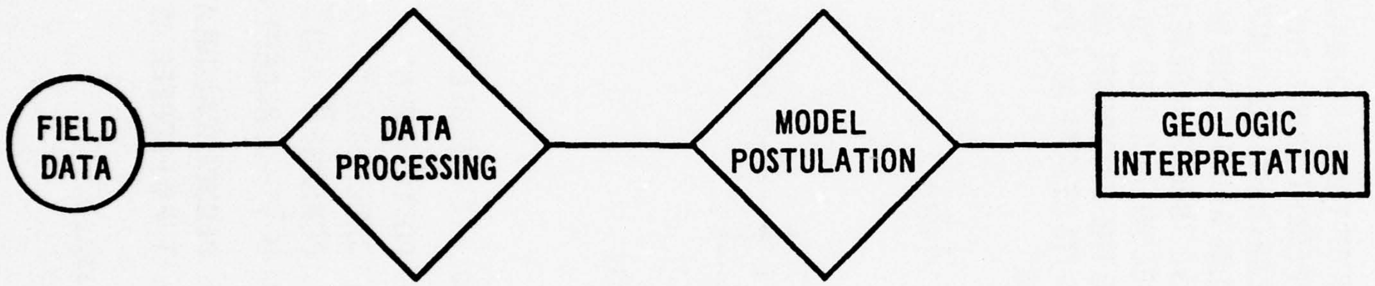
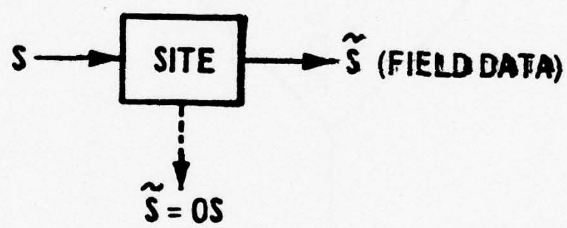

FIELD DATA
DATA PROCESSING
MODEL POSTULATION
GEOLOGIC INTERPRETATION

Figure 2

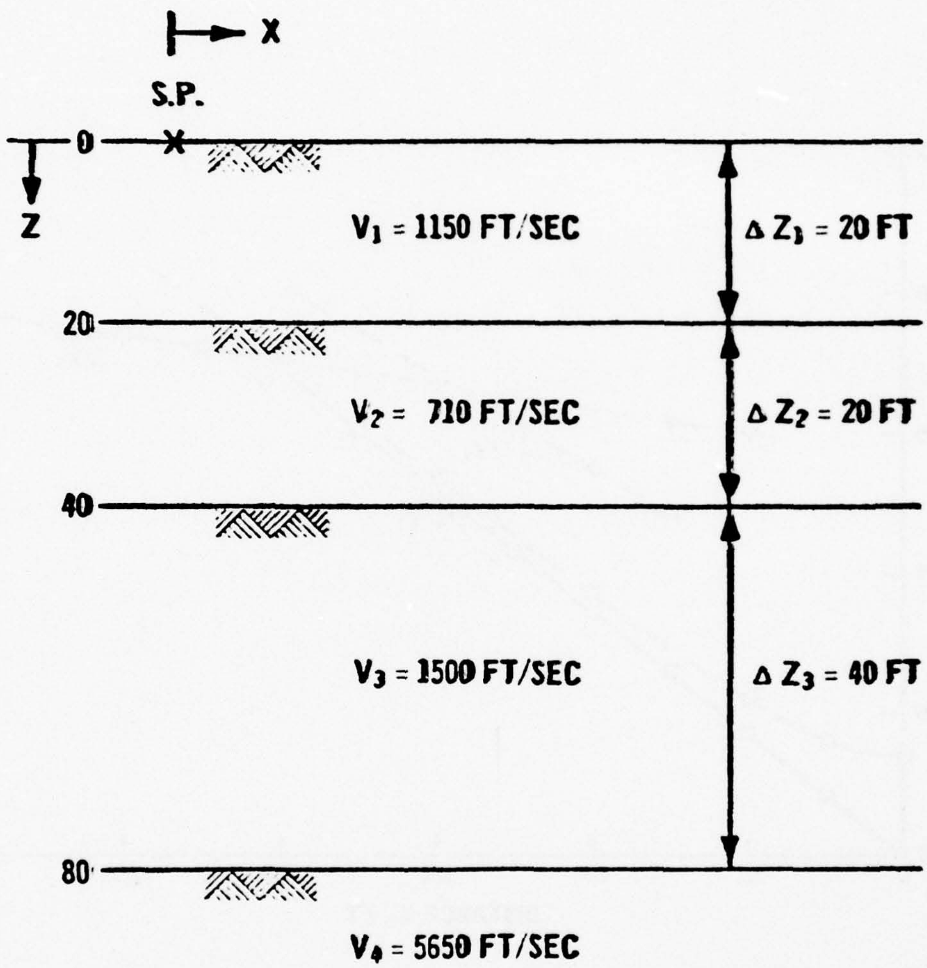
"MANY THEORIES OF THE EARTH HAVE BEEN PROPOUNDED AT DIFFERENT TIMES: THE CENTRAL SUBSTANCE OF THE EARTH HAS BEEN SUPPOSED TO BE FIERY, FLUID, SOLID, AND GASEOUS IN TURN, TILL GEOLOGISTS HAVE TURNED IN DESPAIR FROM THE SUBJECT, AND BECOME INCLINED TO CONFINE THEIR ATTENTION TO THE OUTERMOST CRUST OF THE EARTH, LEAVING ITS CENTRE AS A PLAYGROUND FOR MATHEMATICIANS."

Figure 3



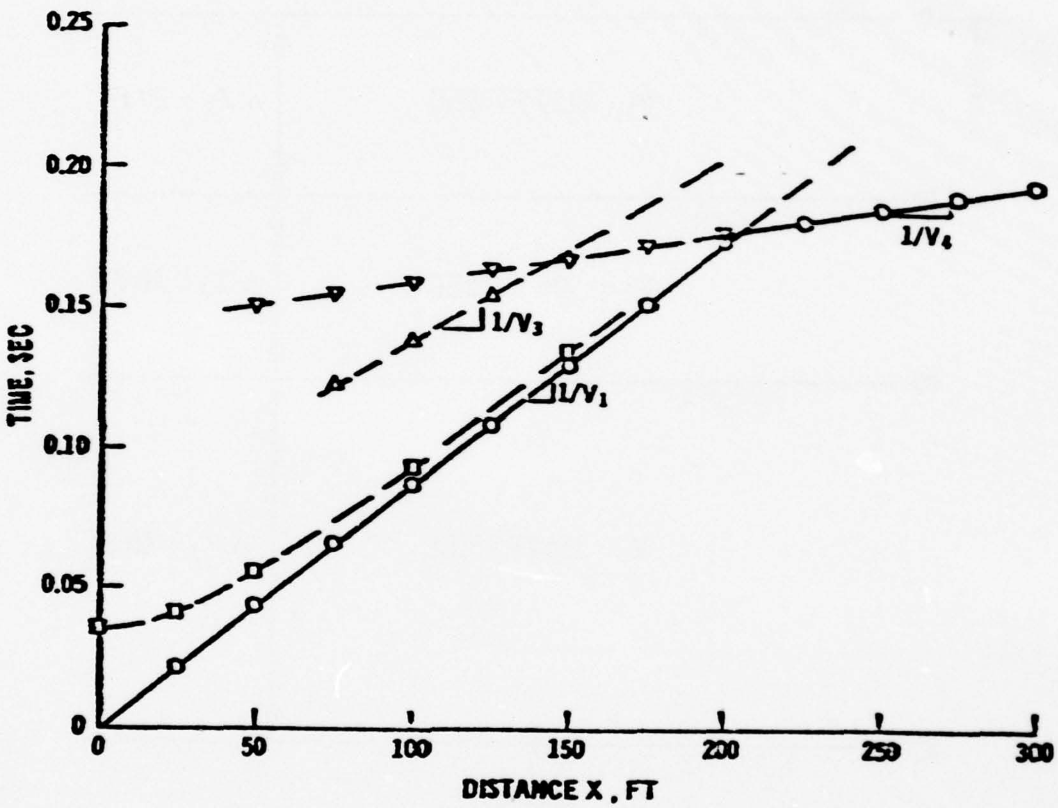
1. POSTULATE OR CALCULATE A MODEL FOR O
2. DIRECT PROBLEM:
   a. POSTULATE O′
   b. CALCULATE $\tilde{S}' = O'S$
   c. COMPARE $\tilde{S}'$ AND $\tilde{S}$
   d. IF $\tilde{S}' \sim \tilde{S}$, ACCEPT $O = O'$
3. INVERSE PROBLEM:
   a. DEDUCE (CALCULATE) O′ FROM $\tilde{S}$
   b. THEN PROCEED AS IN 2

Figure 4



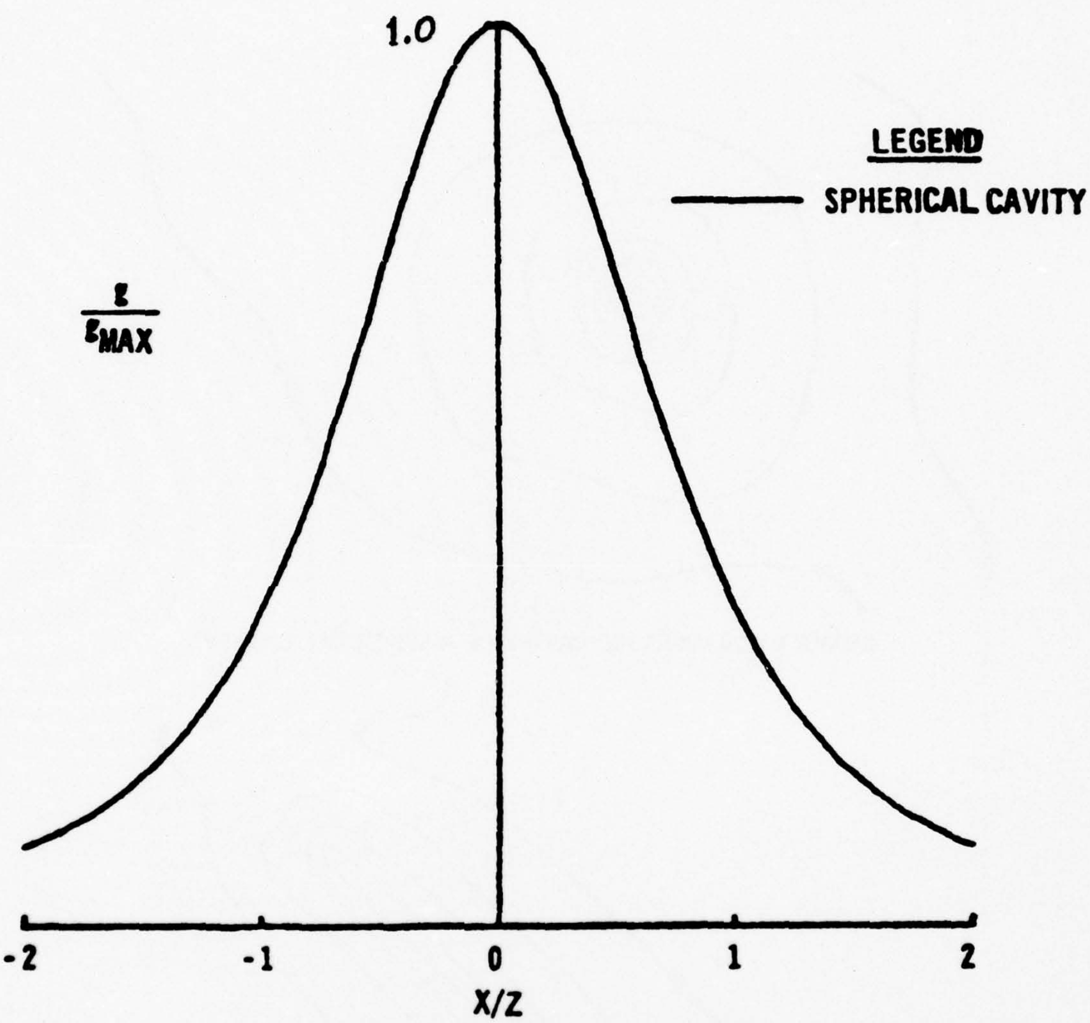
IDEALIZED PROFILE CORRESPONDING TO CROSSHOLE SETS 1 AND 2

Figure 5



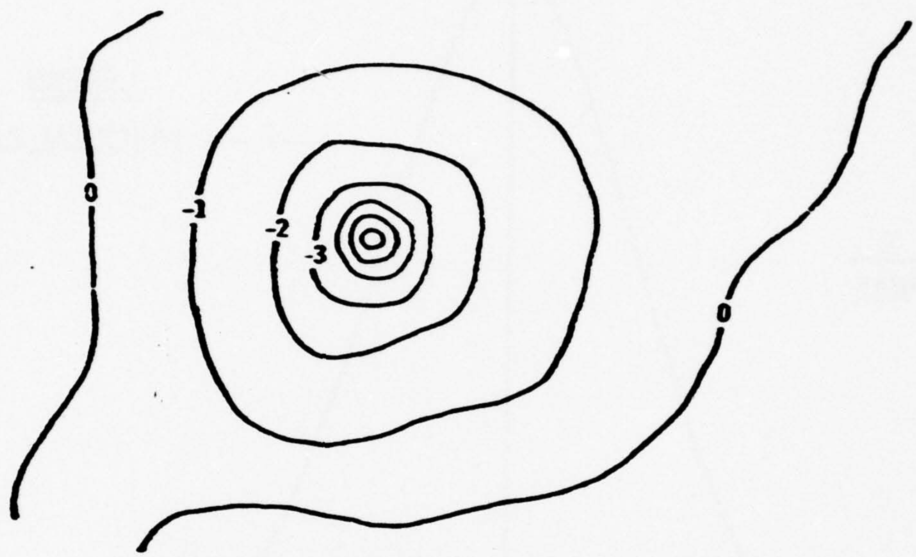
TIME-DISTANCE PLOT FOR HYPOTHETICAL SEISMIC REFRACTION SURVEY OVER THE IDEALIZED PROFILE

Figure 6

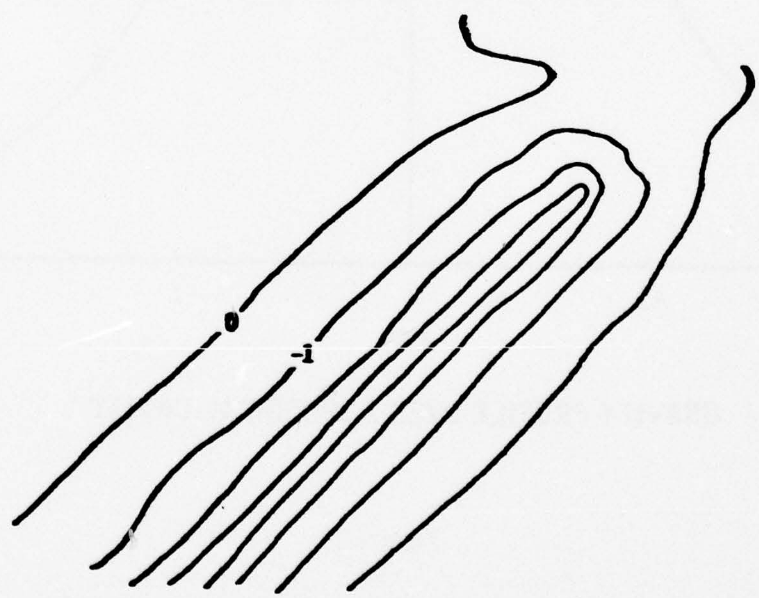


GRAVITY PROFILE OVER A SPHERICAL CAVITY

Figure 7

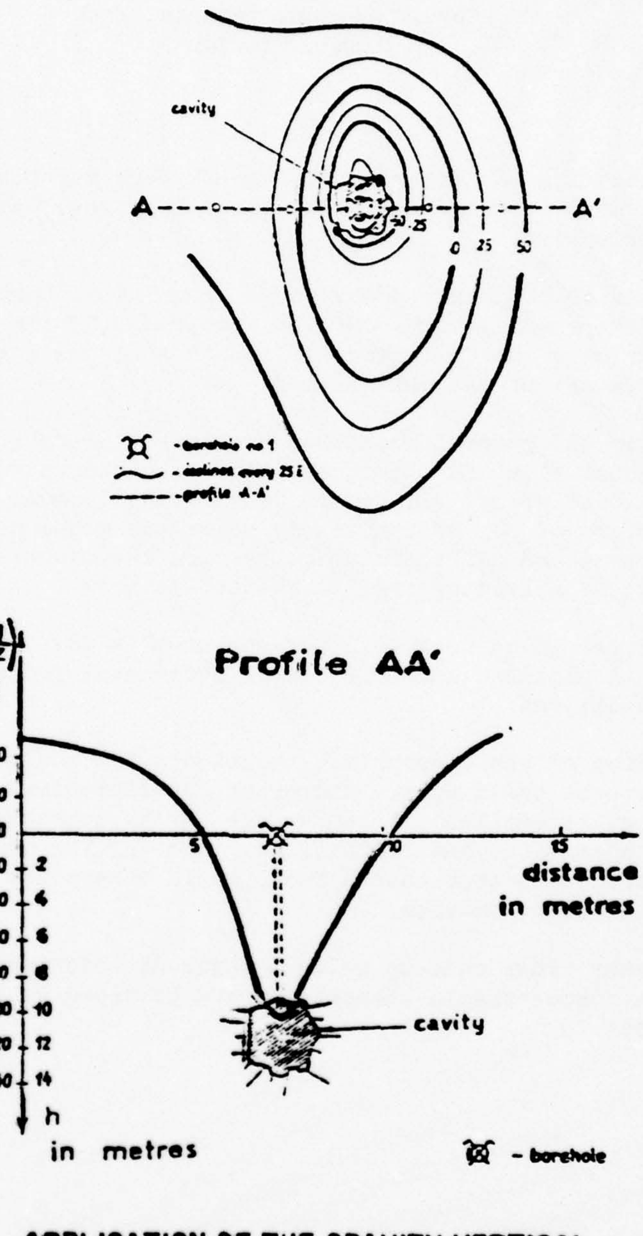


GRAVITY CONTOURS INDICATIVE OF A SPHERICAL CAVITY



GRAVITY CONTOURS INDICATIVE OR TYPICAL OF A HORIZONTAL CYLINDRICAL CAVITY

Figure 8



APPLICATION OF THE GRAVITY VERTICAL GRADIENT TO THE DETECTION OF CAVITIES (FAJKLEWICZ 1976)

Figure 9

AN OVERVIEW OF CAVITY DETECTION METHODS

Richard Benson, Technos, Inc.
Miami, Florida

Abstract

The detection and assessment of subsurface cavities must consider the diverse range of geologic/hydrologic conditions, cavity size, and spatial distribution.

Cavity size of interest may range from 1 to 100 meters in diameter. Their depths may vary over the same range, while their position and shape may vary over a surface of considerable extent. Further, they may be air, water, or sediment filled.

To solve the general case then requires a search for an unknown number of random size and shaped cavities, located randomly over a three dimensional space. If we are considering a small space of say 100 cubic meters or so, we can likely solve the problem in the "absolute" sense and do it economically. On the other hand regional problems must be solved by less "absolute" methods.

Techniques which work well for one problem may fail under other conditions. A simple example is one of underdeveloped areas versus urbanized conditions.

Selection of the appropriate techniques for a given situation must therefore be based upon a number of considerations. A wide range of methodology is available to solve the cavity detection problem. Each has its own advantages and limitations. Some of the techniques may have resolution to better than a foot, while others are only able to detect very large structures.

Cost many times ends up being a major decision making factors in such work. Some simple comparisons are provided as a guideline to such decisions.

AN OVERVIEW OF CAVITY DETECTION METHODS

My presentation of the subsurface cavity problems is based upon geophysical field experience in Florida and the Bahamas. In addition, we have had discussions with numerous persons interested in this problem nationally and internationally.

The problem is global in nature and includes many geological settings other than those discussed herein.

In discussing this problem, I would like to divide my comments into three areas. First, a look at the problem and its diverse nature. Second, a look at the tools available to attack the problem. Third, the approach to the field work.

NOTE: Some figures and photos are not included in this paper.

Part I. The Problem

The cavities of interest may range from small local cavities of less than a foot to more than 100 feet in diameter. We will use the term diameter and think of an equivalent spherical space to represent a localized cavity enlargement. The small ones may be so abundant that they turn the limestone in a virtual Swiss cheese. Figure 1 shows a photo of a very permeable limestone with cavities about 1 centimeter in diameter. Figure 2 shows a limestone mining operation from which the overburden has been cleared. These cavities are typically a foot or two in diameter. The larger ones (Fig. 3) represent voids of more than 15,000 cubic yards. It is difficult to find a driller's log from Florida which does not show some signs of cavities.

GEOLOGIC SETTING

The entire peninsula of Florida consists of multiple beds of limestone from a few to more than 10,000 feet-thick overlying basement rock. A gentle uplift has occurred in the center of the state, creating a draping of these beds with dips to north-south, east-west from the mid-state Ocala area. Limestone exposed at or near the surface is all from the Cenozoic era less than 70 million years old. The surface is covered in many places with thin to thick deposits of clays, quartz sands, and detrital clastic material.

Previous elevated sea level stands are marked by many terraces on the Florida peninsula from five feet to 200 feet or more above mean sea level.

Younger limestone is still forming today in Florida's coastal waters. These younger reef limestones may contain a high degree of void space.

The Ocala uplift produced fracturing of the overlying limestone, leading to further development of cavities by solution.

We see, then, that a wide range of age in Florida's limestone, the interaction of previous sea level stands, and fractures of the Ocala uplift all influence solution and Karstification. In addition, we have the well-developed aquifers with cavernous zones and many springs.

Subaerial dissolution of Florida's limestone proceeds at an estimated rate of 600 tons a day (Skinner 1972);1.5 inches/1,000 years, (Brooke). In addition to solution, we have documented calving of large blocks of limestone. These have also been observed to calve in response to vibration from passing trains or heavy vehicles (Fig. 4).

The problems caused by these sinks range from negligible to dangerous. Fortunately, we know of only two lives lost in Florida because of sinkholes. Some typical problems associated with sinks and cavities concern:

1. Foundations (pilings)
2. Losses of buildings and equipment
3. Damage to utilities and roadways
4. Failures of dams and containment ponds
5. Contamination of ground water
6. General Subsidence

While there are a number of negative aspects associated with the development of cavities and Karst features, there are also some positive ones:

1. Springs

2. Recreation and fishing in lakes

3. Increased real estate values

4. Aquifer storage and transmission

5. May have applications as indicators of tectonic activity

The Florida collapse sites can be grouped into three categories: those with considerable unconsolidated overburden which develop into a piping type collapse; those with little overburden in which a limestone roof collapse occurs; and those in which a combination of roof collapse and piping occur. The piping and combination types of collapse where the overburden may be semi-consolidated seems to be dominant in Florida.

The following are examples of the above:

Fig. 5 - 30-foot diameter (piping collapse) caused by heavy ground water pumping for irrigation and cattle watering.

Fig. 6 - Ben's cave (roof collapse) date and cause unknown.

Fig. 7 - Balm (combination collapse) caused by low annual water level.

Note that voids or cavities may exist in semi-consolidated overburden, as shown in Fig. 7, but the cavity in the limestone was the original factor which allowed the overlying cavity or piping to develop. Pike's work in South Africa has shown that the roof of such structures can support considerable loading.

Many open sinks give clues to past activity and assist in assessing nearby problem areas. A typical open sink will appear as in Fig. 8. The bell shape with debris piled up on the floor is typical and two openings are usually near the bottom from which the

structure originally developed. The plan view of one larger open system (Eagle's Nest) is shown in Fig. 9.

The form of a cavity system can be quite complex as shown by Kuznetsov, Fig. 10. We have observed a number of complex shapes including one well-developed spiral-shaped system. On the other hand we have observed many simpler shapes with geometrical or repeated patterns.

The factors which trigger collapse are of interest. Our Florida State Department of Transportation compiles sinkhole statistics which are primarily roadway-related. Over a ten-year period it lists a total of 224 collapses. The actual occurrences are many times this number but many go undetected or ignored. Of the 224 listed, 92 have had their cause noted.

Fig. 11 - Causes of Collapse

Blasting	5%
Drilling	5%
Low Water Table	8%
Construction	11%
Other	11%
Rain	58%

These sinks are primarily associated with roadways. As such, they are commonly triggered by diversion and channelling of surface runoff. The data show over half were caused by rainfall. Similar situations are commonly found associated with parking lots. (See Figs. 12 and 13.)

To the contrary we have found that larger collapse sites are commonly a result

of a lowered water table, natural and/or man-caused. Within some areas 70 percent of these larger sinks occur in the months of April and May.

A typical annual precipitation cycle for Florida is shown in Fig. 14. During the low rainfall periods the water table is naturally depressed and withdrawal by man may depress it even more. Such a depression caused the sink shown in Fig. 15. Note the depressed water level compared to that in a later year (Fig. 16).

We note then that cavities and sinks and their causes are associated with a wide range of variables. These include geology, both depositional and subsequent actions of nature, as well as man's activities. The "cavity" and its geologic setting can be quite varied in size, shape, and depth.

Considering then that the problem is really quite varied and complex, we cannot view it in any simplistic way.

In considering a "cavity detection problem," we must set some limits when determining our objectives. A simple list of preliminary factors to be considered would include:

* Size of interest (or range of sizes)
* Depth (or range of depths of interest)
* Area limits (local, intermediate, regional)
* Setting (terrain, degree of development, sources of noise, etc.)

Geologic aspects must also be considered. Are we looking at a Paleo Karst feature which is inactive or mature, or is it an actively developing cavity? Cavities may be backfilled with clastic material or they may be open air or water filled. The geologic/hydrologic setting will many times dictate the method of detection.

The areal extent of survey may well be the most important factor in deciding on a technical approach. While an acre of land can be readily assessed for cavities within a period of, say, a week, a section of land being evaluated at the same level would take years. It becomes obvious that we must consider the degree of coverage and probability of detection--while the acre may have coverage and detection probabilities approaching 100 percent, the section of land obviously cannot. The real world is faced with both time and economic constraints which prevent "total coverage" of large areas. It should then become our objective to provide the highest level of coverage consistent with other project requirements.

Although this paper deals with the cavities, fractures, and lineaments associated with limestone, it certainly is not restricted in principle or methods to this material or solution cavities. It is applicable, however, to a wide range of engineering and environmental siting requirements. Cavities or subsidence may be brought about by mechanisms other than solution enlargement of limestone, halite, or gypsum deposits. General subsidence may be caused by withdrawal of geo-fluids and locally by decomposition of organic deposits or hydrocompaction. Piping can develop substantial cavity structures in unconsolidated material.

Part II. Methodology

In a report to the Florida Legislature it was stated that "Geophysical devices and data therefrom are highly interpretive and can be realistically utilized only for very shallow cavities" and "No cheap means is now available to isolate specific small areas as to its relative degree of sinkhole development probability."

One Phd dissertation suggests regarding remote sensing, "An optimum overall technique has yet to be found."

Another master's thesis concludes, "Little is known on how to reliably detect the existence of underground caverns."

I frequently will find a client who states flatly that "them there geophysical methods just don't work." We even hear disagreements between geophysicists on results of various techniques.

These comments seem to present a rather discouraging picture regarding cavity detection. On the other side of the coin we hear reports of eminent success using a wide range of techniques. What are we to believe? What is the truth of the matter?

Our views on the matter are quite simple. All of the established geophysical, engineering, and remote sensing methods work and work well (Fig. 17). And they will all fail under certain conditions. A dilemma? No, it's simply a matter of selecting the correct method for the given situation and using it properly.

As we review the tools available for the job, some of the advantages and limitations will become obvious. We will find that some techniques, while they may provide valid results, may be economically unsuitable to certain tasks. Others simply will fail to work under certain conditions.

The proper tools cannot be selected until due consideration has been given to the project objectives, geologic siting, budget, etc. Only when these factors and others have been reasonably bracketed can we proceed with the choice of suitable methods.

Since this is an overview paper we will not attempt to define the methods and their details technically. We will assume the reader has a fundamental concept of the methods and comment upon the advantages, limitations, resolutions, applications, and costs. The main point of our discussion is to show that a wide range of techniques and approaches are available to solve the cavity detection problem and that the correct selection is dependent upon many factors.

We will classify three methods of cavity detection (see Fig. 18), depending upon sensor location:

Those conducted from "aircraft" (remote sensing).

Those conducted from the surface.

Those conducted beneath the surface.

If one considers surface extent, it is apparent that airborne methods provide the greatest and subsurface methods provide the least lateral coverage. From the resolution point of view, the opposite is true. That is the subsurface methods will generally provide the highest resolution, surface methods next highest, and aerial techniques the least resolution.

Remote Sensing

The remote sensing methods include any form of aerial or space platform.

The format may vary from black and white panchromatic films and color to infra-red or other special films. Besides film format, thermal, multispectral, and radar imagery are available. The result is a wide range of platforms, altitude, and imagery formats are available to assess problems.

Fig. 19 - Remote Sensing

Vehicle	Format	Other Variables
Aircraft	Film Black & White	Altitude
High Altitude (U2)	Color Infra-red	Time of Day
Manned Space Flights		Season
	Thermal	
LandSat		Vegetation Coverage
	Multispectral	
	Radar	

The obvious advantages of remote sensing is that it provides a rapid means of examining the area and developing regional trends. Identification of such features as lineaments, existing sink patterns, vegetation stressed areas, ground water, and geologic regimes may be readily seen in many cases. The methods are relatively easy to use for the solution of simple or obvious problems. On the other hand, for more difficult problems the method may not yield to the most skilled interpreter. In all cases ground truth is a must.

The more subtle the information sought the more critical becomes such aspects as light angle, the time of year, etc. Within the confines of developed areas, the method may fail completely unless some old aerial photos are available. Further within forested areas incipient sinks and more subtle indicators (possibly even the obvious ones) may not be visible. Generally, however, the method in its simpler

forms must be applied to all cavity evaluations.

Fig. 20 - Remote Sensing

Advantages

--Sometimes data is already available and costs can be quite low.

--Provides coverage of large areas (synoptic view).

--Yields Geologic/Hydrologic trends.

Disadvantages

--More advanced techniques require advanced equipment and interpreters.

--Sophisticated techniques can be quite expensive.

--May fail totally in some areas. Such as buildup, forested, etc.

Surface Methods

These methods include a wide range of tools whose means of detection vary considerable. Each method may respond to a different set of physical parameters. Some techniques are restricted in depth of penetration, others work to considerable depths. A number of the methods may be used to develop "regional" data which will indicate potential anomalous areas. They also may be used in a high resolution mode to directly detect cavities.

Fig. 21 - Surface Sensor Methods (Geophysical)

	Regional	Local (cavities)	Resolution	Traverse Speed
Seismic	yes	moderate	low	medium
Resistivity	yes	good	high	medium
Gravity	yes	good	med-high	slow
Ground Pene-trating Radar	shallow	good	high	rapid
Electro Magnetics	very shallow	low	low	rapid
Magnetics	yes	shallow	medium	rapid

There are times when one's objective is not to look for cavities per se, but to develop overall trends where cavities might pose a problem. We refer to such an approach as a "regional" investigation. We use the word regional loosely to imply not only the area of specific investigation but its surrounding areas. The actual area involved is usually relative to the scale of the immediate problem and its importance.

Generally, the geophysical methods sample a volume of space as opposed to a very localized nature of drilling. We therefore obtain a more representative averaging of the geologic characteristics over a sample volume (see Fig. 22).

Portability is also important. Much equipment can be carried in the field, and is easily flown to remote sites.

Usually, the basic principles do not change much; we simply modify them in various ways. There are, of course, exceptions, such as Ground Penetrating Radar which was unavailable 10 years ago. The instruments, however, do change drastically over a decade or so. Vacuum tubes gave way to transistors, which are giving way to integrated circuitry and microprocessors. Along with this dramatic change in technology are improvements to basic materials and data processing methods. The result is that we can do things today we simply could not do five to ten years ago. Equipment is lighter, more portable, and more rugged and in many cases less expensive.

Although we will address ourselves to the problem of cavity detection on land, many of the methods are equally adaptable to water covered areas. As a matter of fact many of the marine methods are high resolution and continuous. This results in a very low cost/unit mile coverage. The marine methods may also be used in fresh water; such an approach can be quite effective if working with a site near lakes, rivers, or coastal areas.

The seismic method responds to variations in the transmission of seismic waves - a function of density and elastic constants of the soil and rock, the resistivity method responds to changes in electrical conductivity within the media. The gravity method responds to changes in density and distribution of material. Ground penetrating radar requires a contrast in dielectric/conductivity characteristics.

1. In each case a contrast in the measured parameter must be associated with the cavity, if it is to be detected.
2. Further, the cavity must be present within a "relatively homogeneous material" if our detection signal to noise ratio is to be high enough as to produce results.
3. The cavity must also have a sufficient size to depth ratio to be detected. As the size/depth ratio becomes smaller, the cavity will become difficult or impossible to detect.

These three factors become an important part of any cavity survey and the geophysicist must be able to judge whether this criteria will be met, for a given case.

Seismic

The seismic methods include standard refraction, fan shooting, and reflection techniques, as well as specialized reverberation/resonance measurements.

Fig. 24 - Seismic

Wave propagation depends upon density and elastic constants of the soil or rock.

Refraction)
) "Regional" or Local
Reflection)

Fan Shooting)
) Local
Resonance/Reverberation)

Fig. 25

Seismic Advantages

* May be used to obtain regional trends.
* Also has applications for direct detection.

Seismic Disadvantages

* Method is subject to noise. (Enhancement seismographs are a great aid in noisy areas.)
* Refraction methods suffer from inverted layer and thin layer problems.

Refraction and fan shooting are useful as indirect detection tools because they provide a quick means of obtaining local geology and variations or anomalous areas. The methods are also useful for direct cavity detection if the cavity is large and not too deep with respect to the seismic line and not masked by higher velocity overlying media.

The shallow engineering reflection methods offer improved resolution to the seismic methods to detect cavities, with smaller size to depth ratios. Here we have a minimum depth restriction associated with masking of the larger and earlier arriving seismic signals.

We have not had an opportunity to work with any of the reverberation/resonance approaches from an instrumentation point of view. However, on numerous occasions we have made field observations of "unusual ground response" over areas of known cavities. Further, we also have observed areas near and surrounding a recent sink to produce a dominant and obvious low frequency response upon impulse loading. We suspect that this phenomenon is associated with unloading of local soil particles in a situation approaching a quick condition.

Resistivity

The standard resistivity methods of sounding and profiling are also useful as an indirect means of cavity detection (see Figs. 26 and 27). Here the methods are used to identify geologic stratigraphy and locate anomalous areas. As with the seismic methods standard sounding and profiling may detect larger cavity structures, fractures, and fault zones.

A high resolution resistivity method such as the modified Bristow provides a means of detecting and providing size/depth and position information on cavities of smaller size/depth ratios. Other high resolution resistivity arrays are also available for specialized applications.

Fig. 26 - Resistivity

Response depends upon changes in electrical conductivity.

Sounding)
Profiling) "Regional" or Local

High Resolution Methods (Local)

- Dipole
- Equipotential
- Bristow (modified)
- Polar

Fig. 27 - Resistivity

Advantages

--Profiling may provide "regional" trends quite rapidly.
--Data may be processed and plotted in the field.
--High resolution methods can locate individual cavities and provide information on size, depth, and location.

Disadvantages

--Fences, buried pipe, etc., nearby may render the technique useless.

Gravity

The standard gravity method may also be used to provide "regional" trends to identify potential problem areas (see Fig. 28). It may also be used to detect very large cavities directly. A microgravity survey, will detect much smaller cavities. Here a more sensitive instrument is utilized and station spacing is decreased to provide increased resolution and greater data density. The gravity method may be used within reason within developed areas without being influenced by man's pipes, cables, and structures. It suffers from being relatively slow, requiring accurate elevation control, and requires a fair bit of data processing and is affected by ground vibrations (see Fig. 29).

Fig. 28 - Gravity

Senses changes in density.

Standard Gravity "Regional"
(some capability to detect larger cavities)

Microgravity (Local)

Fig. 29 - Gravity

Advantages

--May be used in developed areas.

--Information may provide "regional" trends, and/or locate individual cavities depending upon technique.

Disadvantages

--Relatively slow.

--Requires survey crew for tight elevation control and calculations.

--Instrument is subject to vibrations.

Radar

One of the latest methods is that of ground penetrating radar. (See Fig. 30) For shallow work (50 to 100' maximum depth on some Florida sites) it provides continuous coverage with a graphic cross section record in real time. The advantage of such a record produced at 1-4 MPH is obvious. In addition this method provides a high resolution of 1 foot or so. Though it is only effective for shallow work it may solve many of the cavity detection problems either directly or indirectly.

The limitations are those associated with higher frequency electromagnetic propagation. Any factor which increases electrical conductivity will also reduce penetration. Within a brackish to salt water, ground water penetration is drastically reduced. For accurate depth interpretation the system must be calibrated to the geologic column.

Fig. 30 - Radar

Responds to changes in dielectric constant and electrical conductivity.

Advantages

--Rapid traverse (lowest cost/line mile)

--Provides graphic presentation (real time)

--High resolution (better than one foot)

Disadvantages

--Limited penetration

Electromagnetic & Magnetic Methods

Another possible method is the use of lower frequency electromagnetics. Our

experience here is not with cavity detection, but a sophisticated metal detection device. This equipment is patterned after the geophysical electromagnetic systems and was designed for relatively near field work with high conductivity contrasts. Yet when used in a high resolution mode it provides information on ground conductivity and magnetic susceptibility without electrical contact.

Their application is in rapidly mapping near-surface conductivities which would be used as indicators of possible local anomalies and as a means of calibrating and interpreting other data such as the ground penetrating radar. The depth of these methods (using small portable sensors) is limited from a few to 10's of feet. This is mostly dependent on sensor configuration. As a field rule of thumb I believe their lateral resolving power is approximately equal to their depth.

Although we usually think of limestone when we think of features such as cavities, we could indeed have man-made tunnels or even natural fracture zones in an environment where higher magnetic susceptibilities were present. In such cases a magnetometer could provide a means of location.

Such instruments respond to changes in the concentration of magnetic susceptible materials such as Fe_3O_4. These instruments do not require contact with the Earth as they respond to distortions in the Earth's magnetic field. Continuous sampling high sensitivity fluxgate and cesium magnetometers are available which would allow rapid coverage. Both methods are subject to noise from metallic pipes, cables, and structures. This is especially true of magnetometers and their response to man-made ferrous items. Both methods are limited to relatively shallow work.

Subsurface Methods

The subsurface methods are those in which the sensors are below ground level such as Downhole, and Hole to Hole geophysical methods. I will also include various forms of direct sampling such as drilling, augering, etc.

Fig. 31 - Subsurface Methods

Drilling, Augering, etc.

Downhole

Hole to Hole

1. Drilling

The classic approach to most geotechnical problems is to drill, core, auger, washbore, etc. Here we are dealing with a direct measurement, if a core or sample is retrieved. The method is appealing to most geotechnical people because of its intuitive nature. The difficulty in a Karst situation, such as in Florida, is that the lateral and vertical variations may be great over very short distances and,as such,any implied lateral assumptions may be poor at best. There are layer cake exceptions where this may not be the case, however.

It is the cost of direct sampling plus the lateral assumptions which cause us to seek other methods. In comparison geophysical methods might be called volume or space sampling with respect to the point sampling of the drilling methods. A further problem associated with drilling over cavities is that such activity may

trigger a collapse, and in certain cases, such as investigation next to structures this could be undesirable.

The direct sampling methods, whether field observation or drilling, are essential to provide ground truth for all indirect methods. (See Fig. 32). The geophysical methods are intended to fill in the gaps between drill holes by volume sampling and reduce the number of holes required. If used properly the geophysical methods will provide information for the placement of the holes, thereby utilizing the drill hole as a definitive tool rather than an expensive reconnaissance tool, greatly increasing their effectiveness and reducing cost. When using the drill hole to evaluate for cavities, one may accept as evidence the existence of cavities encountered in the drilling log. Conversely the lack of cavities in the log is not proof that they do not exist nearby.

Fig. 32 - Drilling, Augering, Etc.

Respond by direct sampling, loss of drilling fluid pressure, or rate of penetration.

Advantages

--Provides "absolute" information at a point.
--Can provide direct sample.
--Usually very good vertical resolution.
--Used as a means of control and calibration for indirect geophysical methods.

Disadvantages

--Generally the most expensive method.
--May precipitate collapse.
--Difficult to mobilize in inaccessible areas.
--Information only valid at hole.

2. Downhole Methods

These include the common well logging techniques of spontaneous potential, resistivity, and gamma logs. (See Figs. 33, 34 and 35) Not so routinely used are the seismic velocity shear wave measurements, density logs, borehole gravity methods, borehole cameras, video, and scanning sonars. These latter two are useful for evaluating dimensions of cavity zones extending from the borehole.

Recently introduced is the borehole radar probe, which offers the possibility of scanning the volume surrounding a borehole for up to 25 to 100 feet, depending upon electrical conductivity of the ground.

While many of the Downhole methods are limited to very near field measurements they are nevertheless useful in interpretation of other work and indeed will detect cavities associated with or near the borehole within the limits of the individual method. Miscellaneous downhole measurements or probes would include peizometers, thermal probes, or geochemical sampling.

Fig. 34 - Downhole Methods

Well Logging	
S. P.)	
Resistivity)	Very local (lateral and vertical)
Gamma)	
Density)	
V_p & V_s Seismic Waves	Local (surface to sensor depth)
Gravity	"Local"
Radar	(25 to 100' lateral)
Within Cavities	
Borehole cameras	(visibility illumination limited)
Video	" " "
Scanning Sonar	(unlimited in water filled cavities)

Fig. 35 - Downhole Methods

Advantages

--Provides very high resolution near the hole or within a cavity.

--Scanning methods allow mapping of cavity from one penetrating hole.

Disadvantages

--Very localized information.

--Due to drilling requirements and localized nature are expensive/unit area covered.

--Some methods may not be used thru casing.

3. Hole to Hole

These methods involve measurements between two or more bore holes and the detection of an anomalous structure. (Fig. 36 & 37) They generally offer a very high resolution vertically and laterally for detailed cavity analysis over a limited distance usually less than 100 feet.

The seismic methods using P & S waves and hole to hole radar are examples. These methods are applicable to problems of a very local nature, requiring critical siting requirements.

Fig. 37 - Hole to Hole Methods

Seismic V_p and V_s waves

Radar

Advantages

--Provides high resolution within space between holes.

Disadvantages

--Usually restricted to hole to hole dimensions of 10 to 100 feet

--Increased cost due to multiple holes

Costs

Now let's take a look at what can be done in terms of field production rates. Fig. 38 shows the relative production in linear coverage per day or site per day and the field crew size for various exploration methods. The figures given are for accessible sites, and based upon a maximum depth of interest of 100 feet. They are based upon our experience in the field, but should be used only as guidelines.

Fig. 39 compares drilling costs of 2, 5, and \$10/ft. to typical costs of surface geophysical methods; in no case should geophysical costs exceed the maximum limit of \$5/ft.

Generally the cart is before the horse with cavity problems. That is, we don't investigate in detail or utilize the geophysical methods until a problem occurs. As always, a little preventive medicine is well worth the effort.

By utilizing the geophysical methods in an integrated early site evaluation, the project manager would not only obtain warning of potential cavity problems, but would significantly increase his basic site information and do so at a lower cost, particularly if he uses the geophysical techniques to plan his drilling program.

Fig. 38 - Typical Field Production Rates

Method	Production Rate/Day	Crew Size
Refraction (500' lines end to end)	3,000'	2
Shallow Reflection (40' station spacing)	1,000'	2
Resistivity Profiling (regional)	5,000'	3
Resistivity High Resolution	300-800'	3
Gravity (regional) (station spacing)	300-15,000'	2 + survey
Micro Gravity (cavity) (station spacing)	30-1,500'	2 + survey
Radar	5 to 20 miles	2-3
Marine Continuous Profiling and Side Scan	25 to 50 miles	2-3
Marine Refraction	3,000 to 6,000'	3
Drilling	2-3 sites/day	2
Downhole (includes drilling, etc.)	2-3 sites/day	4
Hole to Hole (includes drilling, etc.)	2-3 sites/day	4

Part III. Assessing The Problem And Putting It All Together

We are commonly asked which method we recommend for cavity detection. There is no way to answer that simple question without investigating the nature of the problem. In one case we may recommend one method and in another a completely different approach. The suggested approach may well encompass more than one geophysical technique as well as a drilling program. We are convinced that to believe a single method will solve all your cavity problems is asking for failure. Don't expect too much from any single method.

Furthermore, it is unlikely that a single method will evolve which will solve all cavity detection problems.

We see the problem as being one of three types in terms of surface coverage.

1. Very localized problems in which a high level of resolution and confidence is usually required for structural purposes. It may be preconstruction information or postconstruction evaluation. Examples are dams, nuclear power plants, and major structures. On such work the detection probability will be quite high and may approach 100 percent.
2. Intermediate size areas in which a detailed assessment is made at selected sites within the area of interest. An example would be limited roadway corridor assessment or airport runways. Here the detection probability can also be at a high level locally, but the entire area is not covered.

3. Regional areas which may range from a section of land to a county. Here the problem remains the same but the solution cannot. One simply cannot investigate such large areas at the same level of coverage and confidence as we can in handling localized problems. We must therefore utilize other approaches.

The results of a regional survey will always be of a regional nature. If sufficient data is available, a reasonable probability can be assigned to the risk factor. Only in those areas examined in detail can we draw conclusions with a high level of confidence as to the existence of cavities. The regional problem depends very highly upon integration of a wide scope of information from many techniques and fields of study and the experience of the interpreter.

Our interest has been in expanding upon the statistical knowledge of cavities within certain geologic regimes. Characteristic size, depth, and patterns seem to appear through the maze of overall variations. We feel that such information is vital to the effective evaluation of regional and even local sites. It enables us to provide better probability estimates and to select our geophysical tools and tune them to look for specific characteristics. This approach takes some of the randomness out of the search problem, making it more cost-effective and feasible.

Our approach is threefold: First, to develop a regional picture of the site attempting to consider as many of the specific

and related variables as possible, and utilizing a variety of techniques and skilled people. This work would usually include aerial photos, interpretation and field work, including direct and geophysical methods. At this point we will have developed a good "regional" picture of the geologic/hydrologic regime, and have identified problem areas and trends, (not necessarily specific cavities).

Second, we would examine problem areas with low resolution reconnaissance methods in an attempt to zero in on the cavities.

Third, we would then locate cavities within those problem areas utilizing higher resolution methods.

At the end of any phase we may render an opinion as to the extent of the problem and probabilities of collapse. The key to zeroing in on the "regional" problem is to develop meaningful trends. An understanding of the physical and chemical factors associated with cavity development on that site is critical. This includes the field of dynamic geomorphology and soil mechanics. Statistical trends in size, shape, spatial distribution, are all important to the geophysical field work as well as any predictive assessment.

For example, if a depth to a subsurface conduit can be established within an area and the cavity size and periodicity established, then these factors can be used to construct survey parameters for these features. In doing this we have taken a

considerable bit of randomness out of the general search problem. (See Fig. 40 Alacuha Sink.) Such characteristic trends may be typical of certain geologic regimes. This fact may allow lateral extension of the field work and statistical predictions with considerable confidence and significantly lower costs. Keep in mind that the regional problem cannot be solved totally with 100 percent confidence. The objective then is to optimize the work such as to provide the best possible coverage and prediction at the lowest costs.

Let me return briefly to the case of the intermediate size areas. Usually the client speaks of detecting cavities and he hopes to achieve a detection level of 100 percent. Let us assume this objective is met, and we have located one or two cavities under an aircraft runway. Is that all there is to the project? Why did they form in the first place? What's the chance of other occurrences; is there a solution to prevent or minimize reoccurrences? This is where the "regional" look is important. I am not suggesting that we must examine a whole county in order to answer the question. Much information can be obtained without a major effort to zero in on an assessment of the problem. Concentration on the detection of cavities alone may not be the optimum approach to a problem.

Some Final Comments

Cavities can be quite diverse in size, depth, location, and overall pattern. They may occur within a mixed and variable geologic setting. Collapse may be triggered by numerous causes. We must somehow better understand the phenomena and the statistics in order to conduct an effective survey and make a meaningful recommendation. The diversity of the cavity problem requires an optimum selection of detection methods.

A wide array of proven methods are available. They all work and they all fail under certain conditions. Generally it is a mistake to suggest that any single method is the answer to all problems. A multiple approach is obviously better and significantly improves confidence levels. Don't expect too much from any single method. You may be kidding yourself.

Drilling or other forms of direct sampling are necessary for ground truth. Yet drilling should be used cautiously as it in itself may trigger collapse. Furthermore, lack of a cavity in a drill log in no way implies that cavities are not present.

Initial in field interpretation is a great asset to quality control and providing feedback to improve subsequent field work. This is entirely possible for some of the methods and impractical for others.

Don't develop a habit of becoming an armchair geologist, using topos, aerial photos, and reference material. Get out into the field if you want results. Ground truth is a must.

Rigid contractual specifications can render a cavity detection survey useless. The field party is obliged to run the items under contract which may be the wrong

approach as one develops trends in field data and experience on site. Many times a client or contracts will indicate specific methods, sites, etc. While any competent geophysicist can run such data, the geophysical methods do not stand alone. They require a good knowledge of the geology and variables which may affect interpretation. Hire someone you have confidence in to solve the problem, not just to run the geophysical measurements.

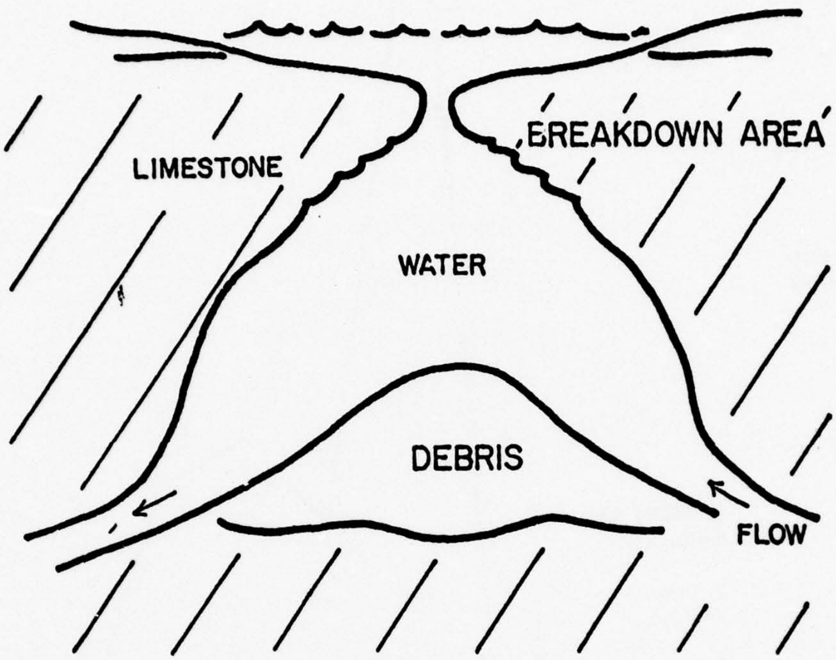


Figure 8. Cross section--typical open sink

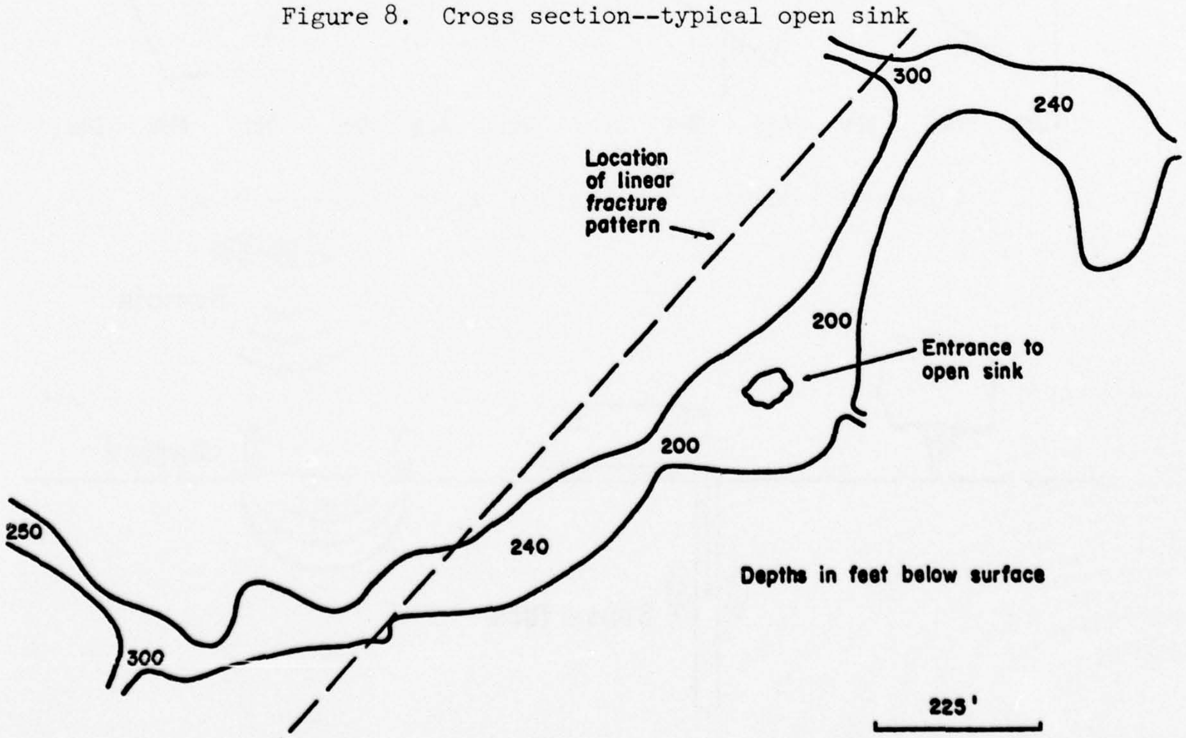


Figure 9. Plan view of eagles nest, after S. Exley

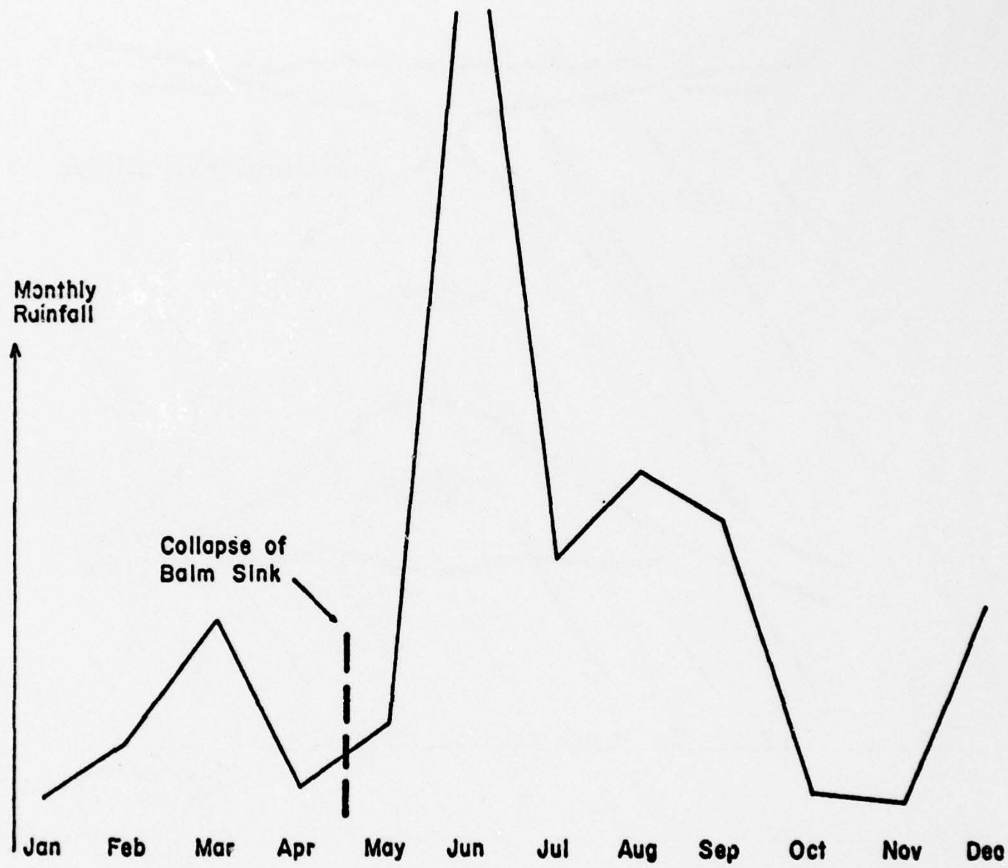


Figure 12. Monthly rainfall, S. E. Hillsborough County

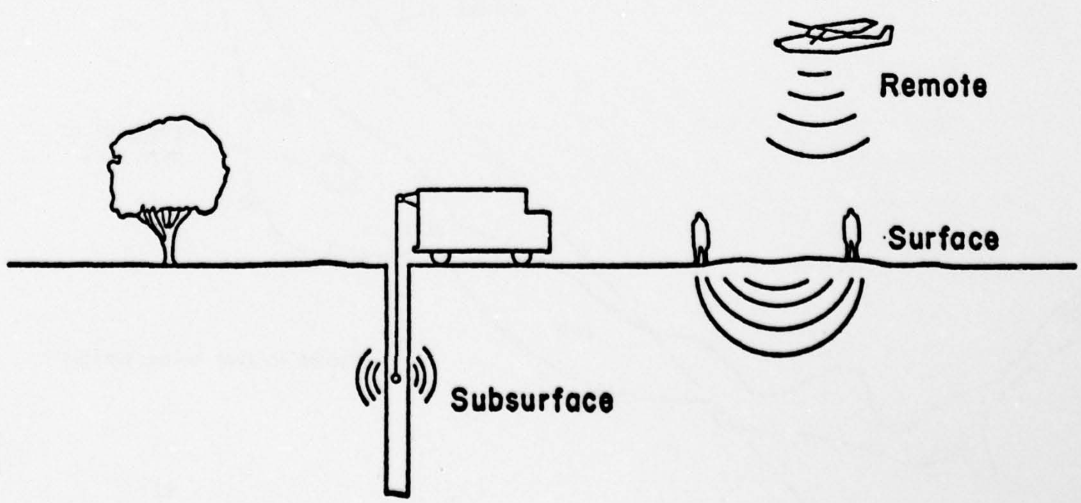


Figure 18. Three methods of cavity detection

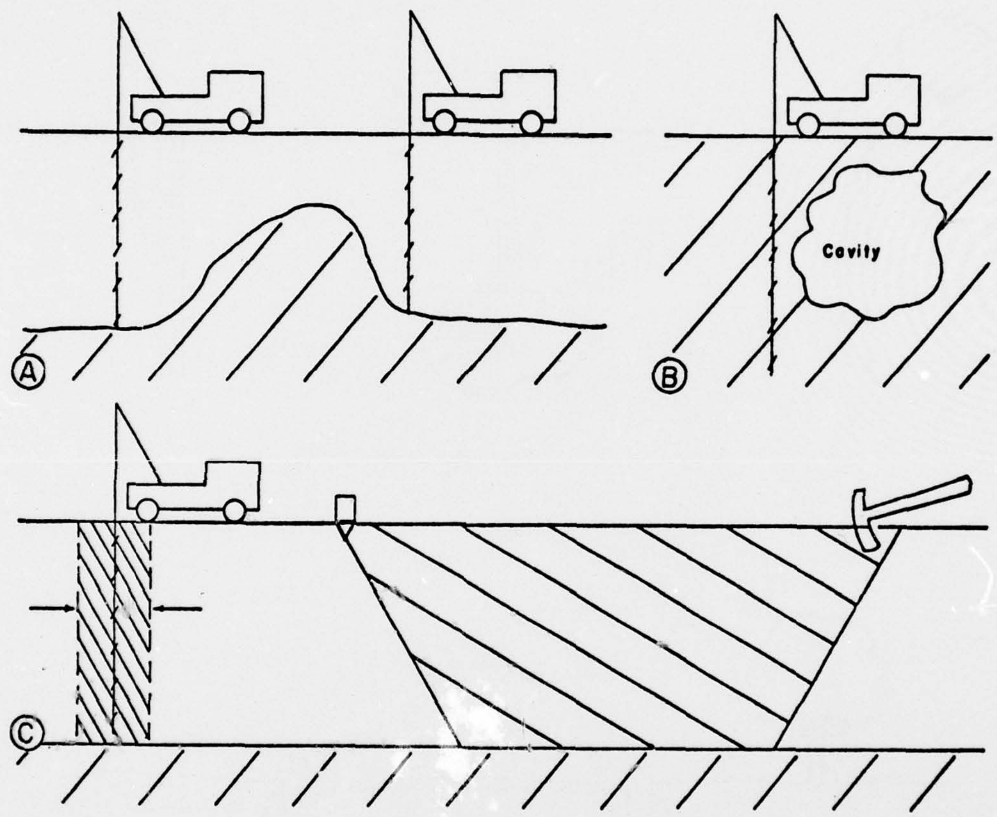


Figure 22. Discrete drill sampling versus bulk geophysical methods

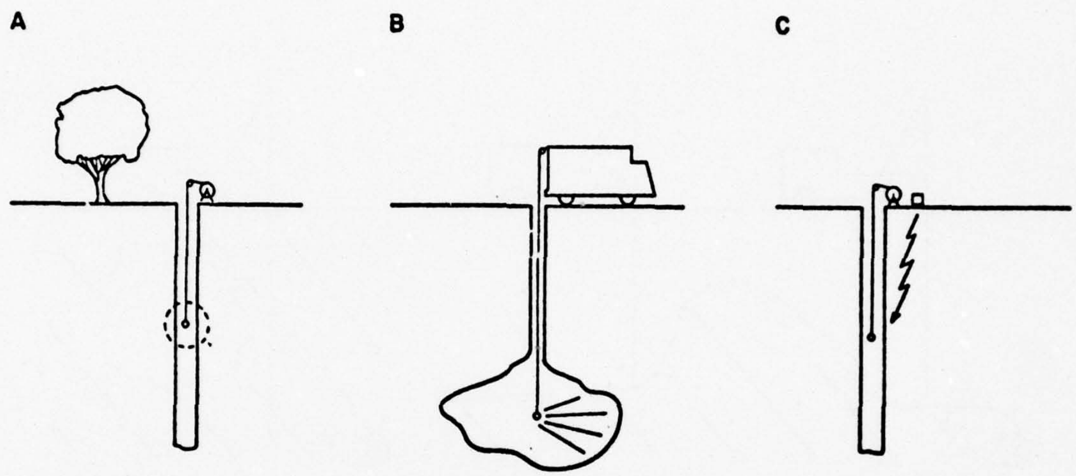


Figure 33. Down hole methods

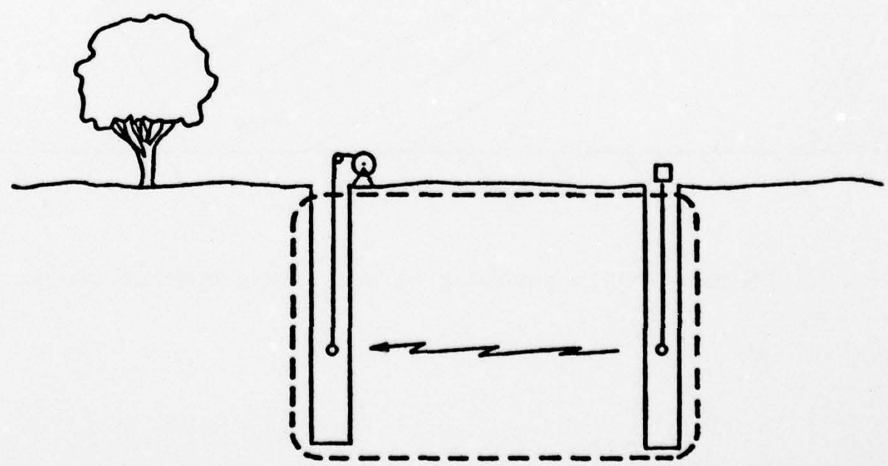


Figure 36. Hole to hole method

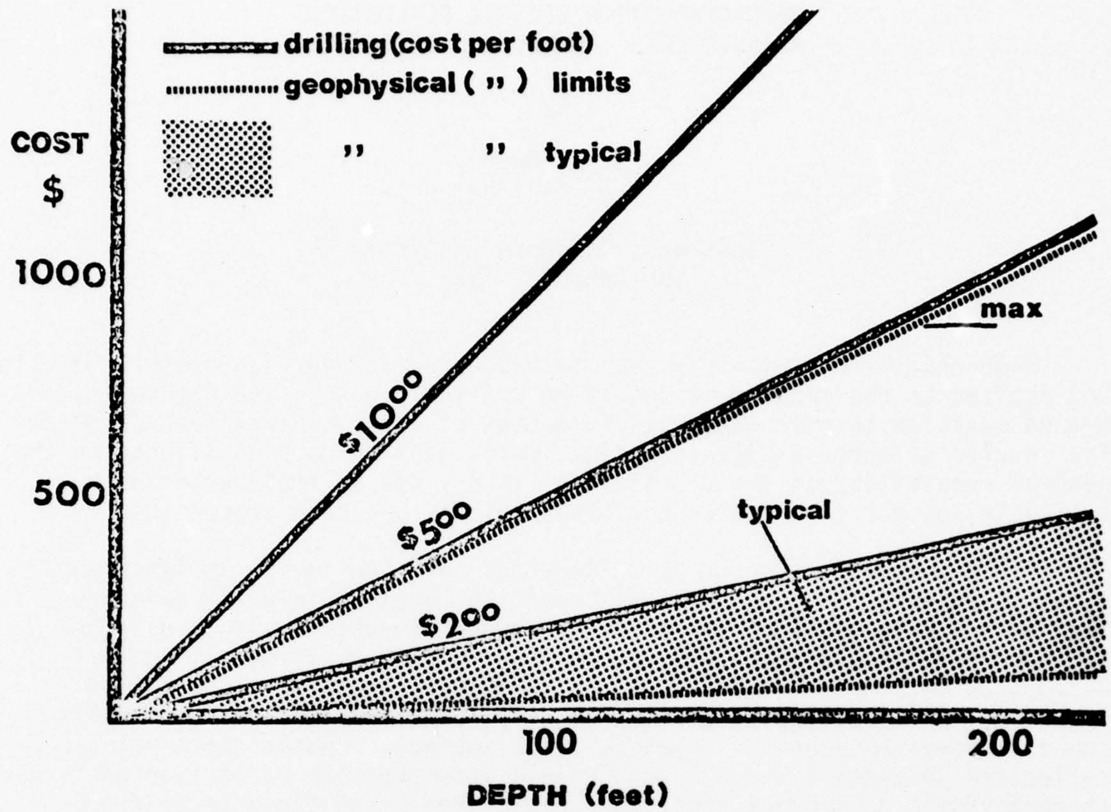


Figure 39

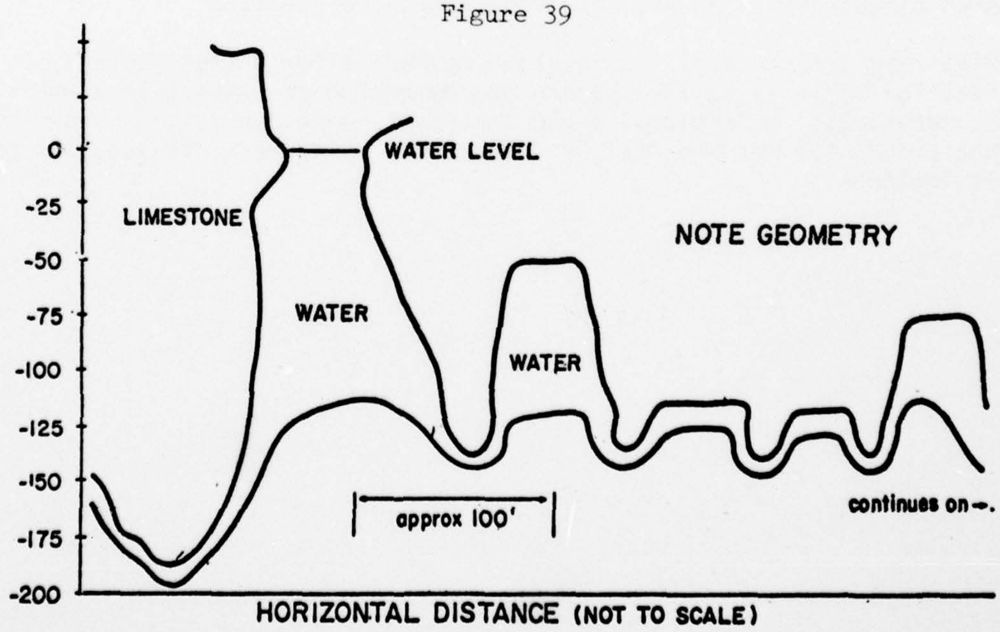


Figure 40. Alachua sink schematic sketch of cross section
(T. Mount-NACD-S. Cawthon)

HIGH-RESOLUTION SEISMIC REFLECTION MEASUREMENTS FOR TUNNEL DETECTION

by

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G.T. Darilek

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High-resolution seismic survey techniques have been successfully developed and applied to the problem of detecting man-made tunnels and natural underground cavities in rock materials to depths of a few hundred feet below surface. The results of three exploratory field tests will be used to illustrate the general feasibility of the technique as it may now be implemented using available seismic exploration equipment systems and data processing.

Field surveys conducted at a limestone solution cavity in Texas and at an inactive Colorado gold mine in granite resulted in valid evidence that narrow cave passages and hard rock tunnel targets could be detected and resolved using seismic signals in the 700-1500 Hz frequency range. Hydrophone detectors and small explosive shots in shallow water-filled boreholes were employed to achieve high-frequency reflection response from tunnel targets as deep as 50 meters below surface. Common depth point reflection processing was used to produce interpretable reflection patterns characteristic of slender localized voids. Processed field records and predicted target responses will be illustrated and compared.

High-resolution seismic exploration methods offer a significant potential for military surface search and detection of subversive tunnels in rock materials. Operational field equipment, data acquisition techniques, and data processing methods will be defined for military field applications and requirements.

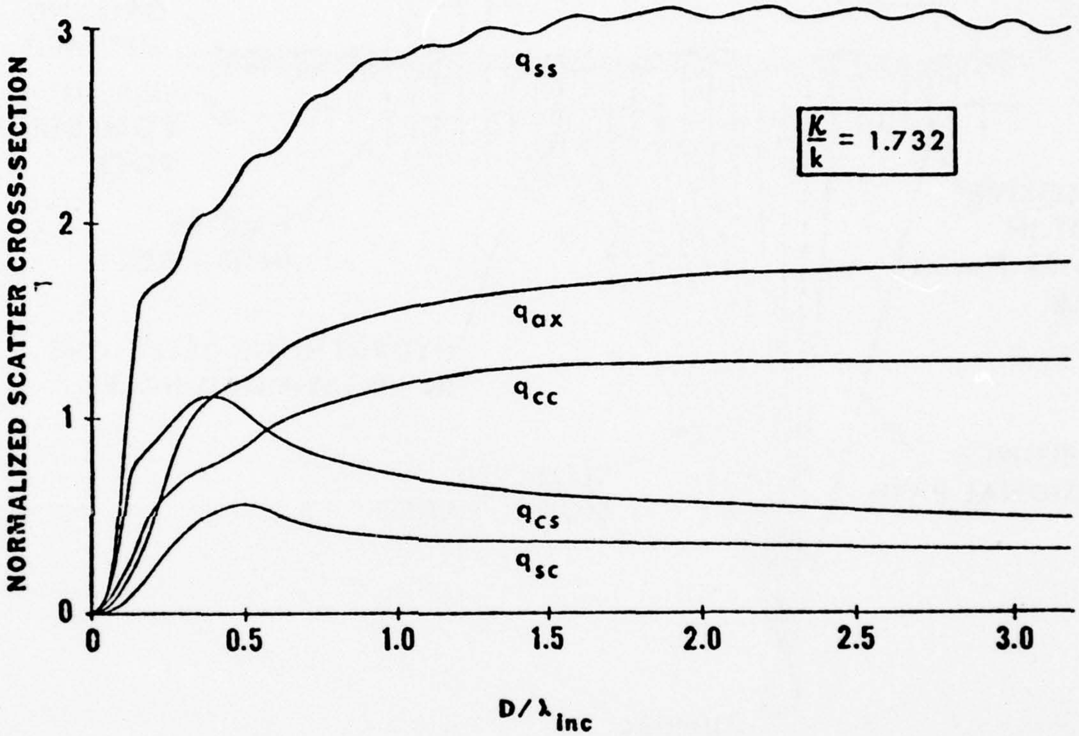

FIGURE 1
NORMALIZED SEISMIC SCATTERING CROSS-SECTIONS OF A
CYLINDRICAL CAVITY IN A ROCK MEDIUM

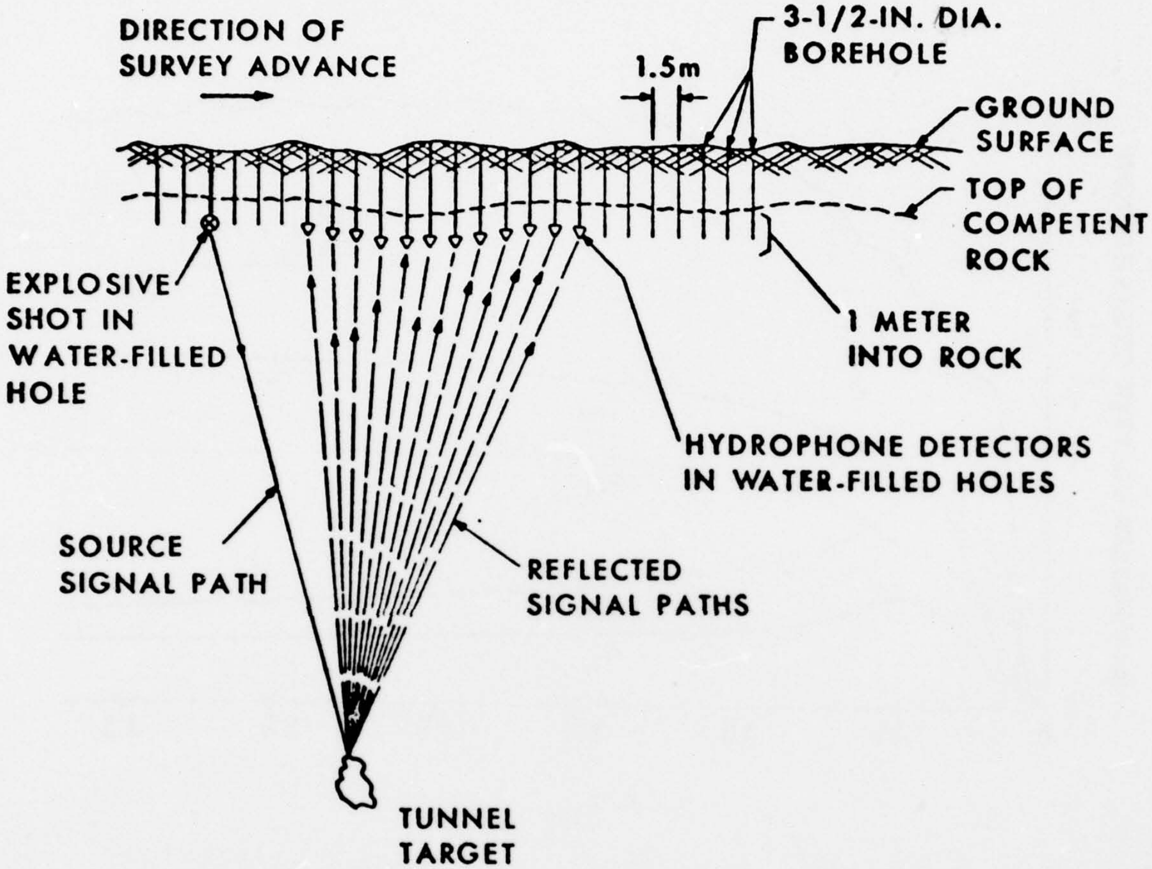

FIGURE 2
FIELD LAYOUT FOR HIGH-RESOLUTION SEISMIC
REFLECTION SURVEY FOR TUNNEL DETECTION

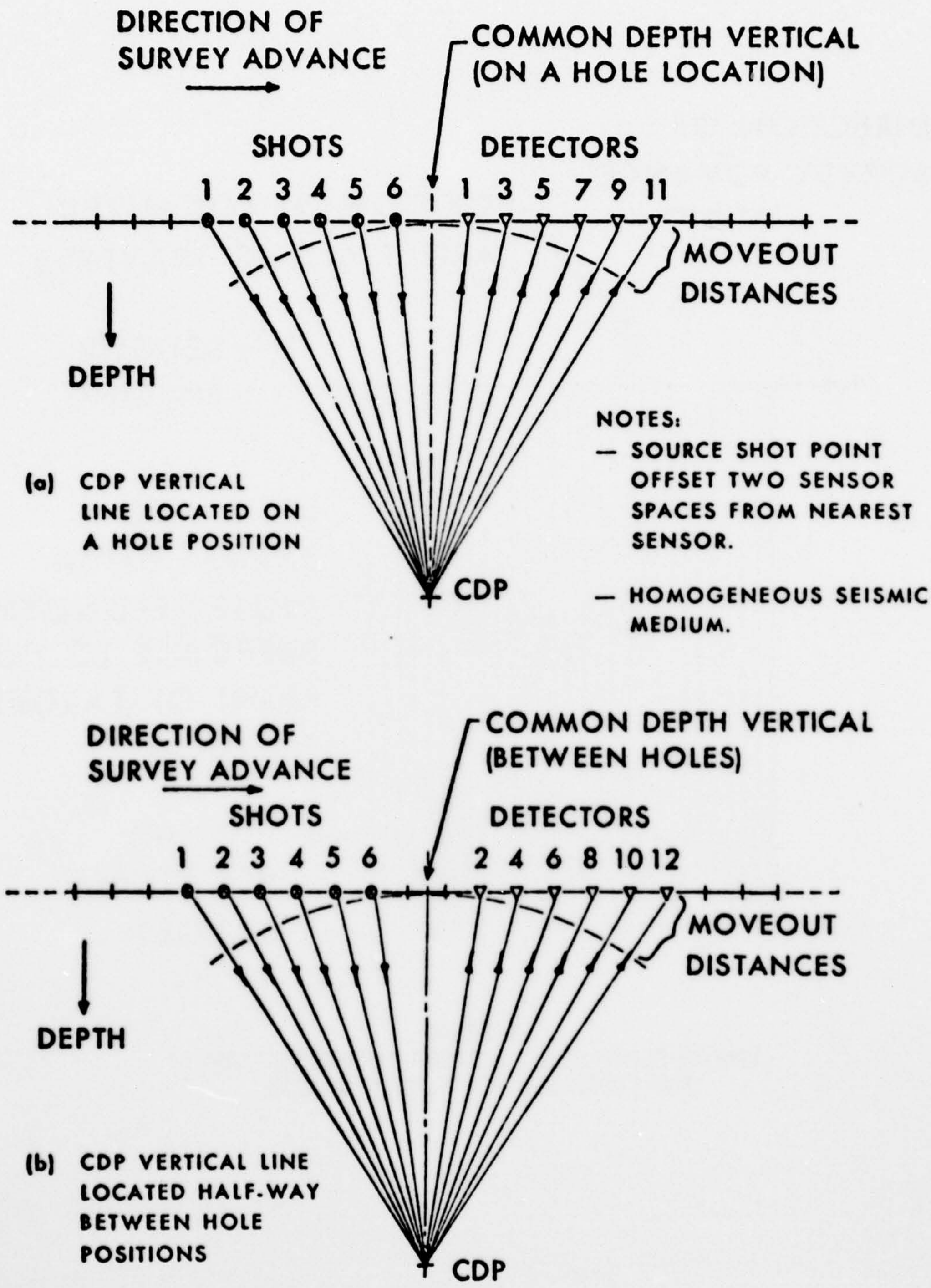

FIGURE 3
COMMON DEPTH POINT GATHERS FOR A 12-SENSOR DETECTION SPREAD AND SIX SUCCESSIVE SHOTS

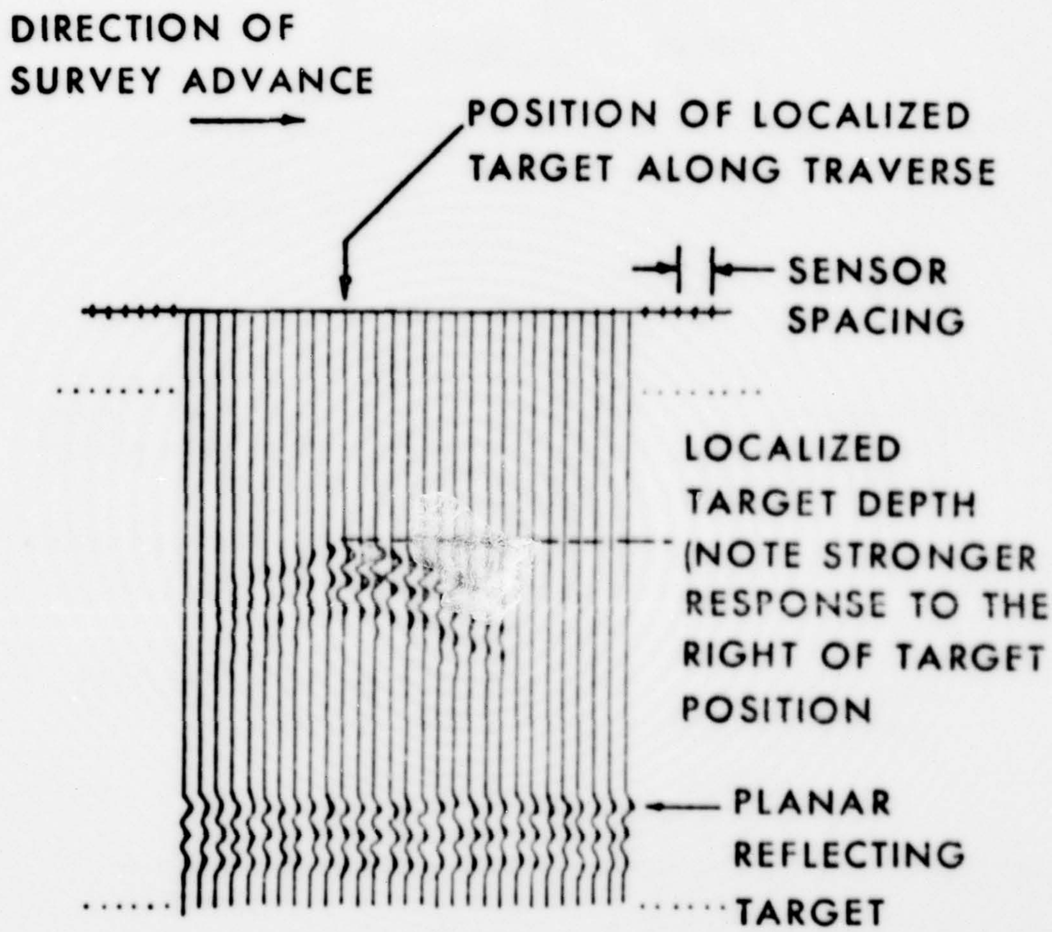

FIGURE 4
COMMON DEPTH POINT DISPLAY REPRESENTATION
FOR LOCALIZED AND PLANAR TARGETS

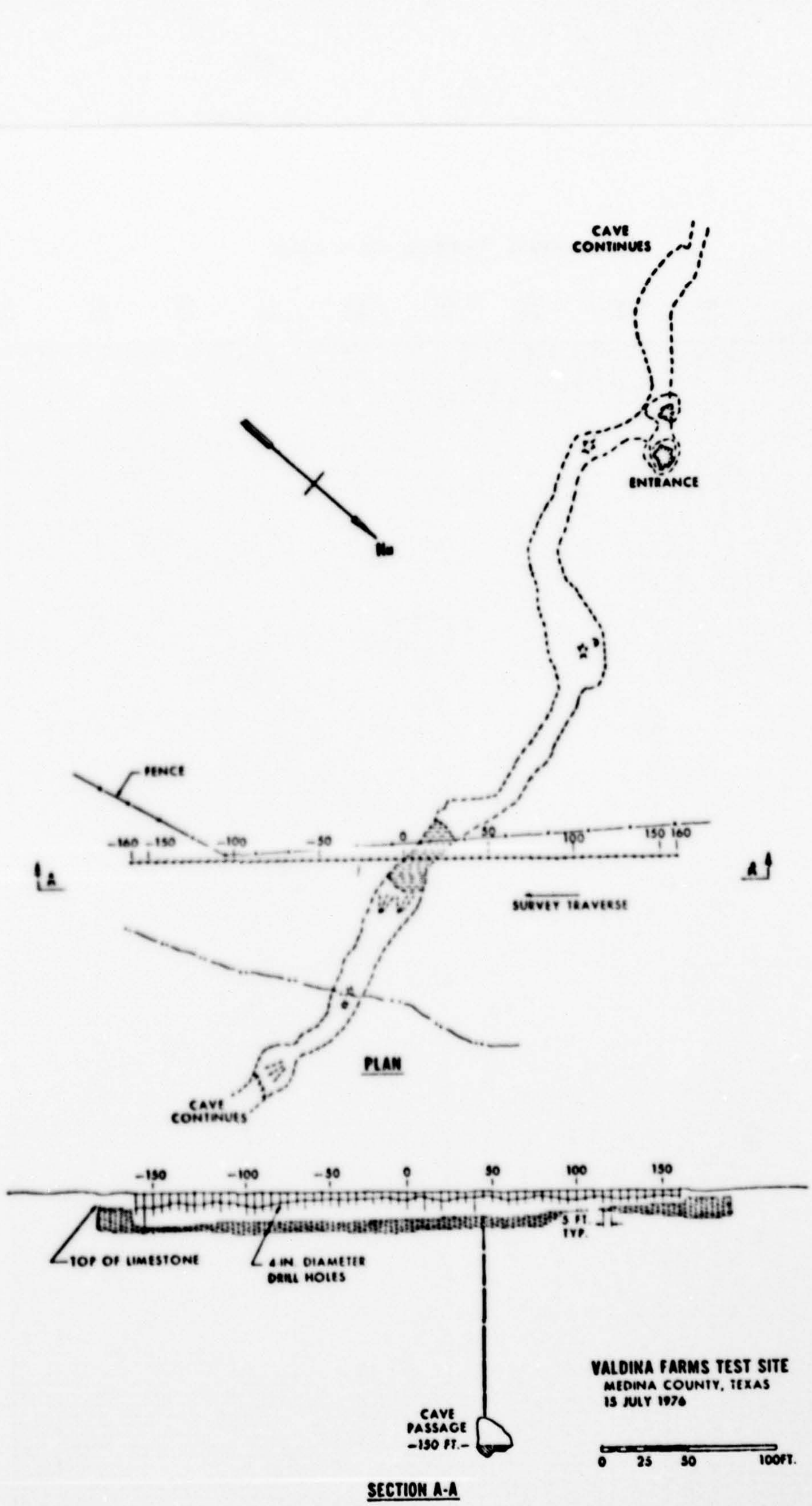

FIGURE 5
VALDINA FARMS TEST SITE

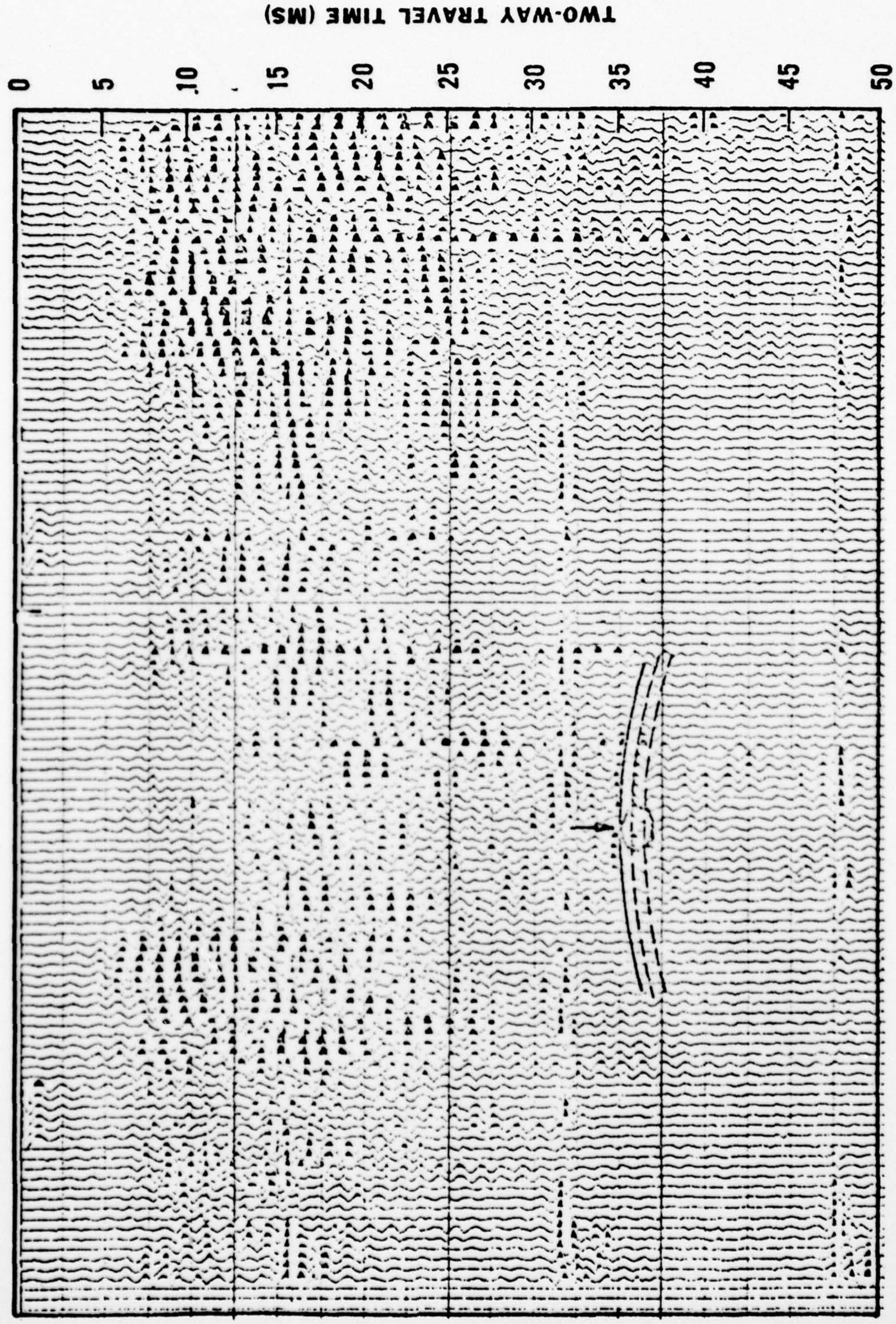

FIGURE 6
VALDINA FARMS TEST SITE RESULTS - FIELD TEST NO. 1

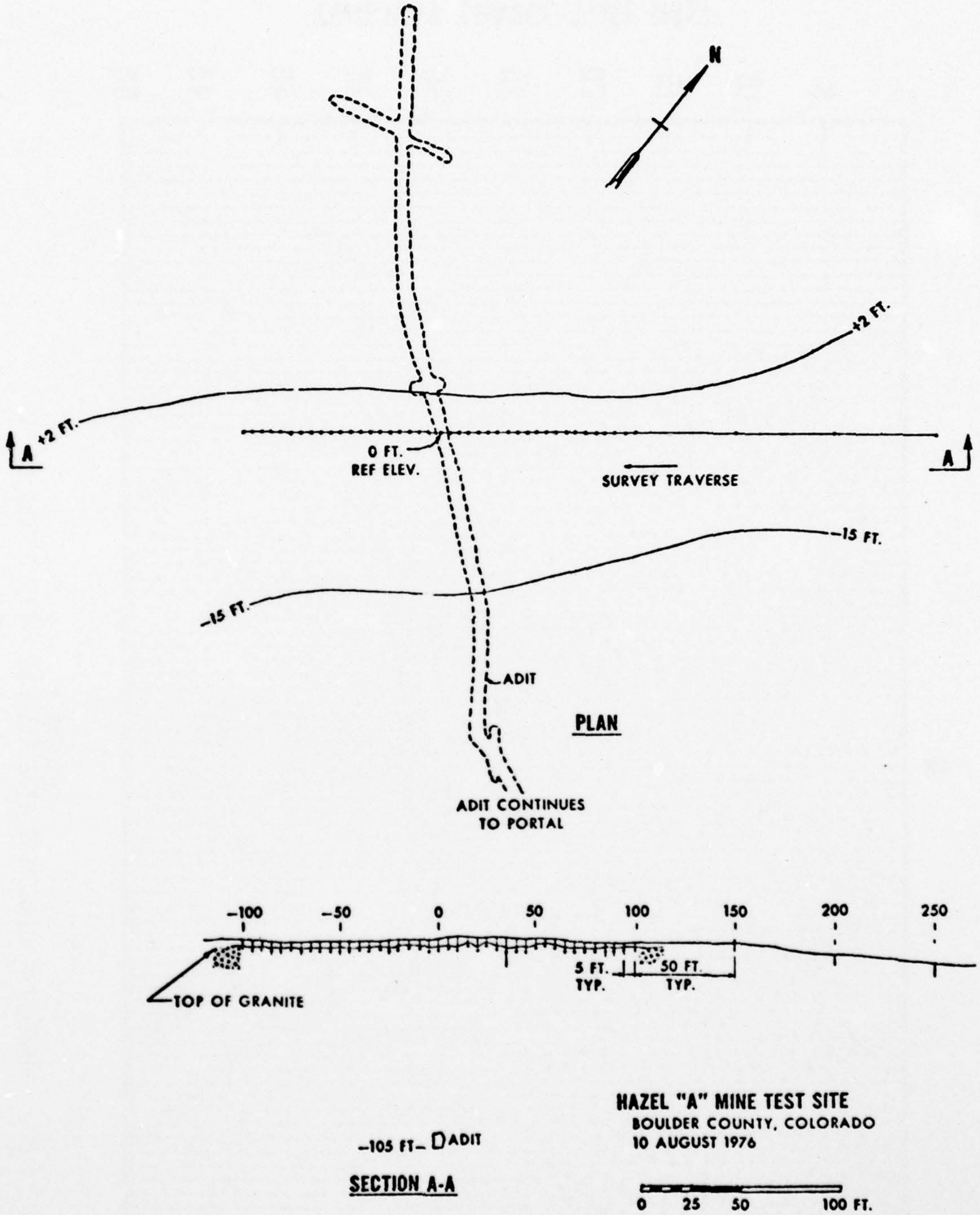

FIGURE 7
HAZEL "A" MINE TEST SITE

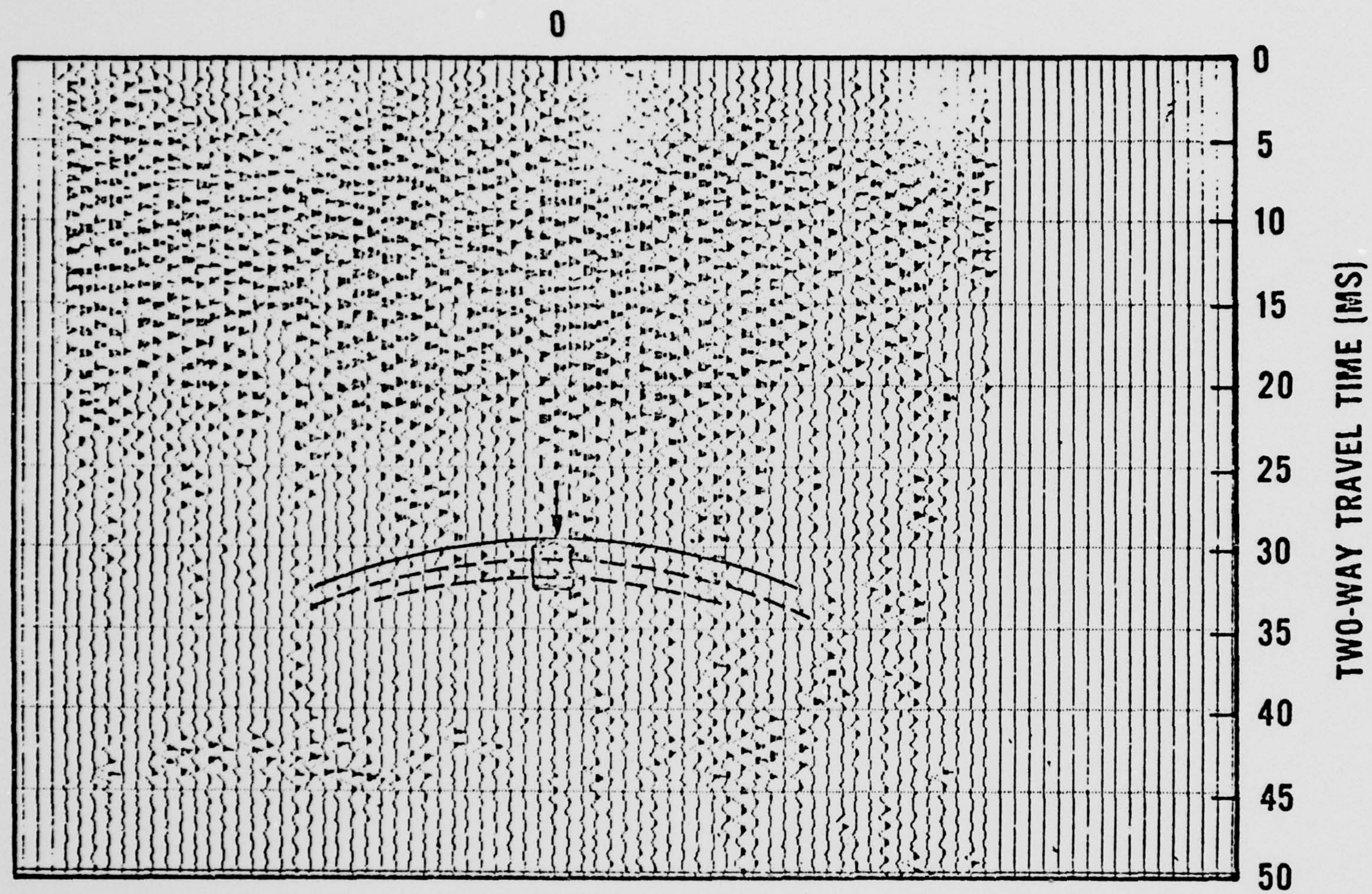

FIGURE 8
HAZEL "A" MINE TEST SITE RESULTS - FIELD TEST NO. 2

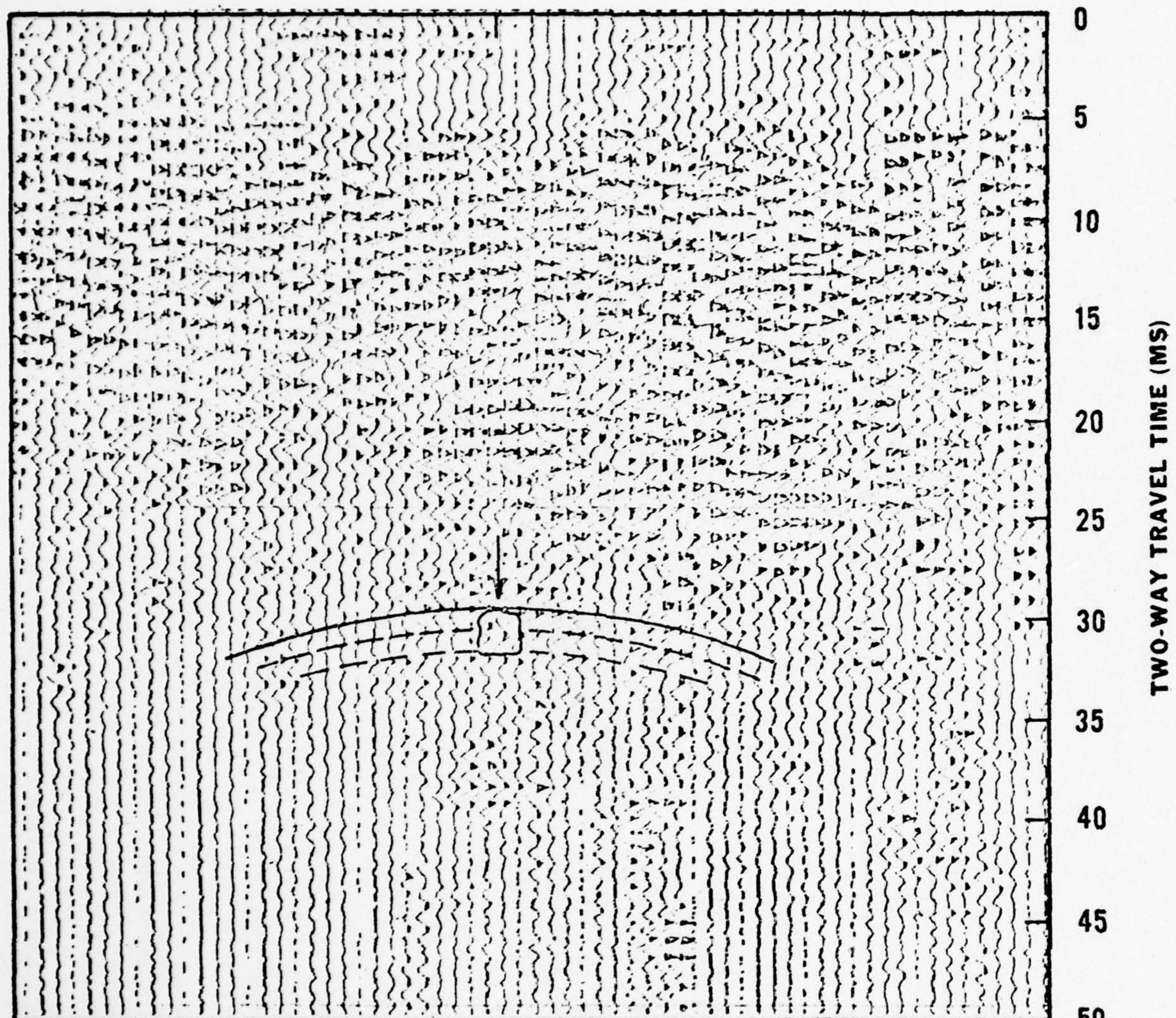

FIGURE 9
HAZEL "A" MINE TEST SITE RESULTS - FIELD TEST NO. 3

SYMPOSIUM ON DETECTION OF SUBSURFACE CAVITIES; DEVELOPMENT OF A PULSE ECHO TECHNIQUE FOR VOID DETECTION IN CONCRETE STRUCTURES

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Abstract

An NDT device needed for detecting voids and discontinuities and locating inaccessible surfaces in concrete structures, using the pulse echo technique, is briefly described. Commercial systems are only capable of length determinations in inches rather than in tens of feet, as is the case with many concrete structures.

A number of factors hinder the development of such an NDT device. First, concrete is a highly attenuating material to a stress wave propagating relatively large distances. Two types of attenuation cause the poor transmission; damping and resonance of the pulse with the aggregate particles. Commercial systems do not have the power to overcome damping, and the wavelength is in the range of the dimensions of the aggregate particles producing resonance. Finally, the transducers used in systems that make transmission measurements in large structures are not adaptable for pulse echo measurements because the transducers resonate, obscuring the arrival of reflected waves.

These problems were overcome with the following system. The stress pulse was generated by an elastic impact from a small hammer or steel ball. The energy from an impact is sufficient to overcome the effects of damping, and the wavelength can be controlled by the configuration of the impactor, preventing the effects of resonance. A crystal transducer was used that did not resonate and had a uniform response with frequency. Since the generated stress pulse was transient rather than repetitive, it was advantageous to use a digital processing oscilloscope rather than the conventional type.

Two types of phenomena associated with stress wave propagation are being considered to detect voids in concrete structures. First is the concept of fixed and free surfaces. Stress pulses reverse in polarity when a reflection occurs at a fixed surface. At a free surface, a compression pulse reflects as a pulse of unreversed polarity. This information should be helpful in characterizing a hidden surface.

Variations of the transmission coefficient with the acoustic impedance of the material behind the concrete may be an important phenomenon in detecting subsurface conditions. Some materials refract through the subsurface boundary more energy than they reflect from it according to the ratio of the acoustic impedance of the concrete and the material below the subsurface boundary. The measurement amplitude

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of the reflected pulses could yield valuable information as to the type of material below the concrete, such as air, water, soil, rock, etc.

Various length determinations of controlled laboratory concrete specimens have been verified using the system. Length determinations of piles lying in a construction yard and driven piles supporting a structure have been made successfully. Length determinations made on piles beneath a wharf in Kingsland, Georgia, revealed that added instrumentation is necessary to permit unambiguous interpretations of measurements in a complex three-dimensional structure.

The system can be refined with a few modifications. Commercially available transducers will produce less noise. A digital tape recorder is needed to make later interpretations in the laboratory. Various electronic statistical techniques are available to eliminate unwanted reflections and spurious signals. Spectrum analysis and signal correlation techniques are examples.

Only limited tests of length determinations have been made so far. The system has excellent potential for detecting voids, discontinuities, faults, and cracks in concrete structures and their substrates. NDT techniques offer the best solution for determining subsurface conditions.

EFFECTS OF SUBSURFACE CAVITIES ON WAVEFRONT DIAGRAMS

A. G. Franklin

Waterways Experiment Station

The use of the wavefront diagram for the interpretation of uphole refraction seismic data was described by R. Meissner in 1961. A series of shots at various depths in a single borehole is used with a line of surface geophones extending away from the hole. The first-arrival time for each shot/geophone combination is plotted, on a diagram of the vertical plane through the borehole and the geophone line, at a point vertically below the geophone and at the same elevation as the shot. Equal-time contours drawn on the diagram can represent instantaneous wave fronts for a single fictitious shot at the top of the boring, in either of two cases: where the ground consists of 1) horizontally stratified layers, or 2) vertically stratified layers.

In conditions other than the simply stratified case, the contours on the Meissner Diagram do not represent wavefronts. The diagram is still a useful and convenient way of presenting the data, and interpretation partially on the basis of the wavefront analogy usually is possible. However, anomalies should not be interpreted on the basis of wavefront behavior, since it is precisely in those areas that the wavefront analogy breaks down.

To gain some insight for interpretation of anomalies in the Meissner Diagram, travel times have been computed and Meissner Diagrams generated for some simple hypothetical cases involving features that would produce perturbations of the Meissner Diagram. If we can eventually produce a compendium of such examples, it would give us a basis for the interpretation of different kinds of anomalies.

Figure 1 shows an ideal two-layer case, with a 10-foot overburden with a P-wave velocity of 2,000 fps, overlying bedrock with a P-wave velocity of 18,000 fps. The contours have been generated by computer. Figure 2 shows a hypothetical Meissner Diagram for the same condition except that a 10 x 60-foot void is included. To help in studying the anomaly itself, we can generate an "anomaly diagram" by contouring the differences between the times of Figures 1 and 2. This is shown in Figure 3. Note that the anomaly in the plot is displaced from the position of the void, and has a maximum value of about 0.9 ms. Figures 4 through 8 show similar diagrams for a 14-ft square void and a channel-like depression in the rock surface, such as might be imagined to be produced by solution widening and infilling of a joint. We may note that the anomaly produced by the 14-foot void is only about 0.1 ms, which is practically undetectable in the present state of the art.

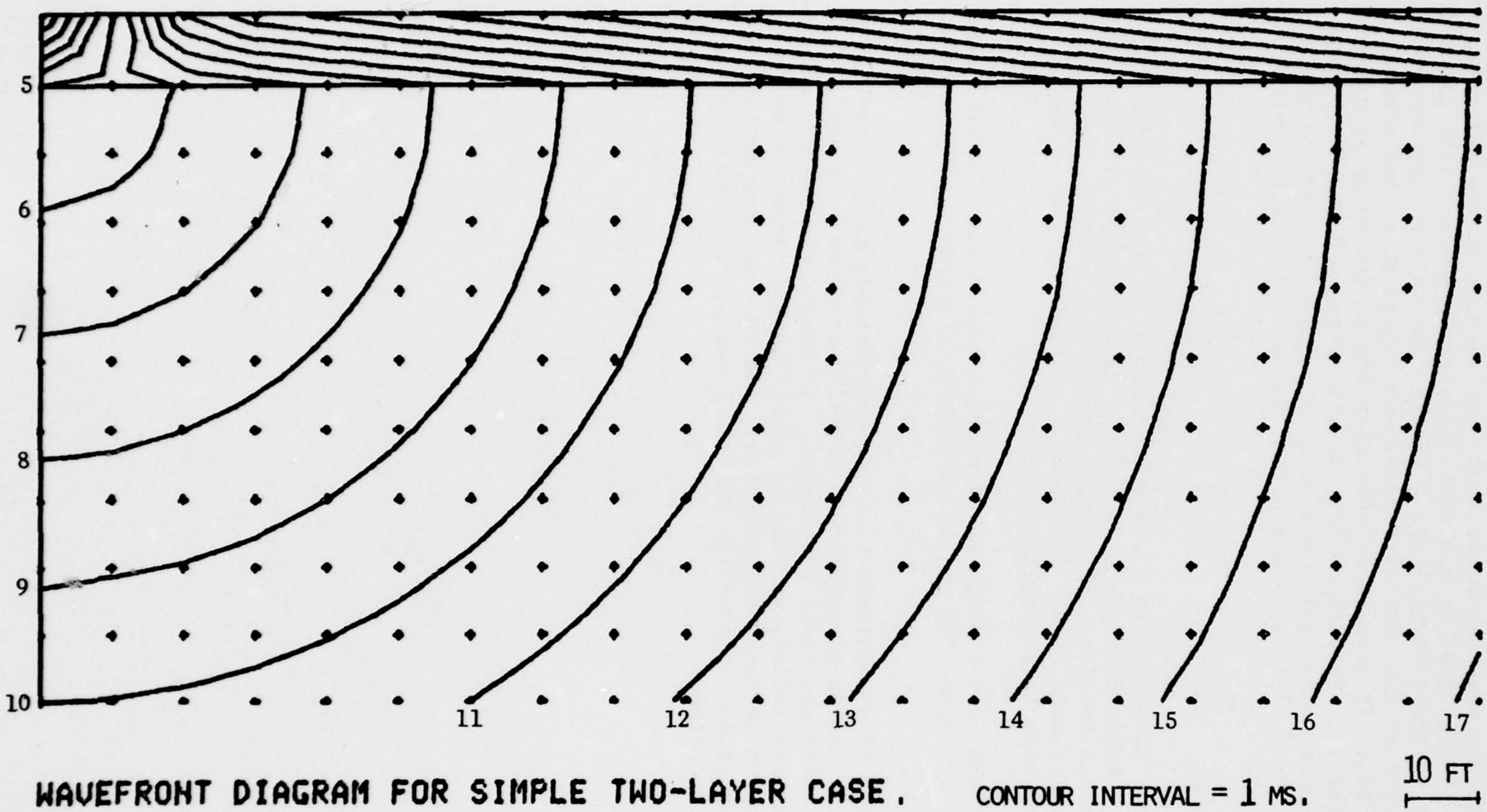
Diagrams of the same kinds are shown for surveys at the WES site, where a cavity is simulated by a 4-foot diameter by 20-foot long piece of PVC pipe buried in the loessial soil. Figure 9 shows a survey across a nearby line that does not cross the pipe, and Figure 10 a line across the pipe. The time differences between them are contoured as an anomaly diagram in Figure 11. Comparison of this with Figures 5 and 8 suggests that the pipe is not detectable, but an 8 ms anomaly is produced by the disturbance of the soil in the trench that has been backfilled over the pipe.

Conclusions:

1. Meissner Diagrams can be useful in exploring for cavities, but their correct interpretation is not straightforward. Interpretation can be aided by "anomaly diagrams," in which the travel-time components due to the known or supposed non-anomalous conditions have been subtracted out.

2. Variations in the depth of overburden have a strong effect, and so the configuration of the soil-rock interface must be accurately defined.

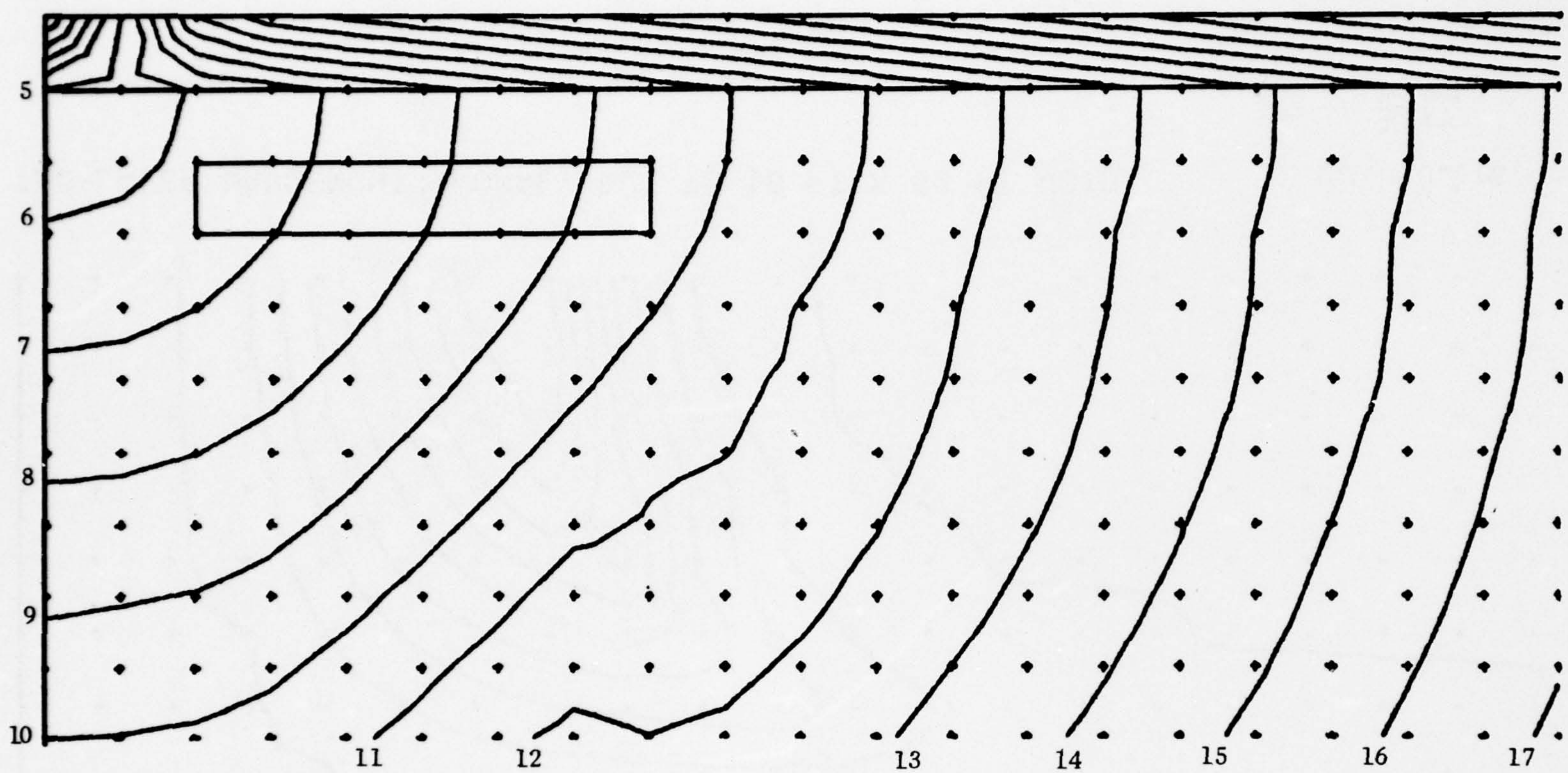
3. Cavities of significant size are undetectable by this method, with the degree of resolution normally attained by today's instruments and field procedures. To obtain the needed improvement in resolution, we need to significantly improve time resolution in our instrumentation, and increase the spatial density of data collection points (i.e., put the geophones closer together).



WAVEFRONT DIAGRAM FOR SIMPLE TWO-LAYER CASE. CONTOUR INTERVAL = 1 MS.

V_1 = 2,000 FPS
V_2 = 18,000 FPS

FIG. 1

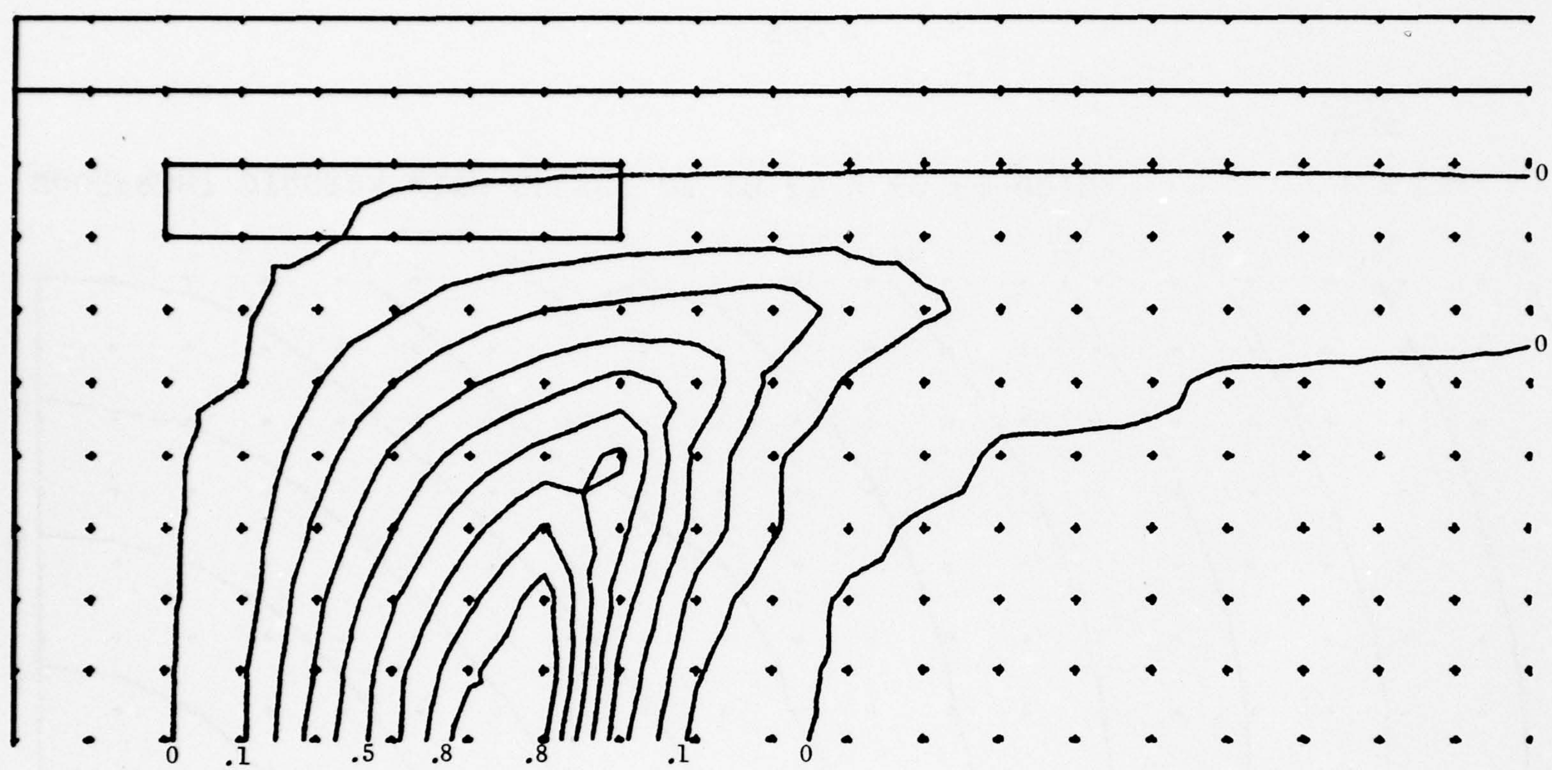


WAVEFRONT DIAGRAM WITH EFFECT OF 10 FT X 60 FT VOID

C.I. = 1 MS.

10 FT

FIG. 2

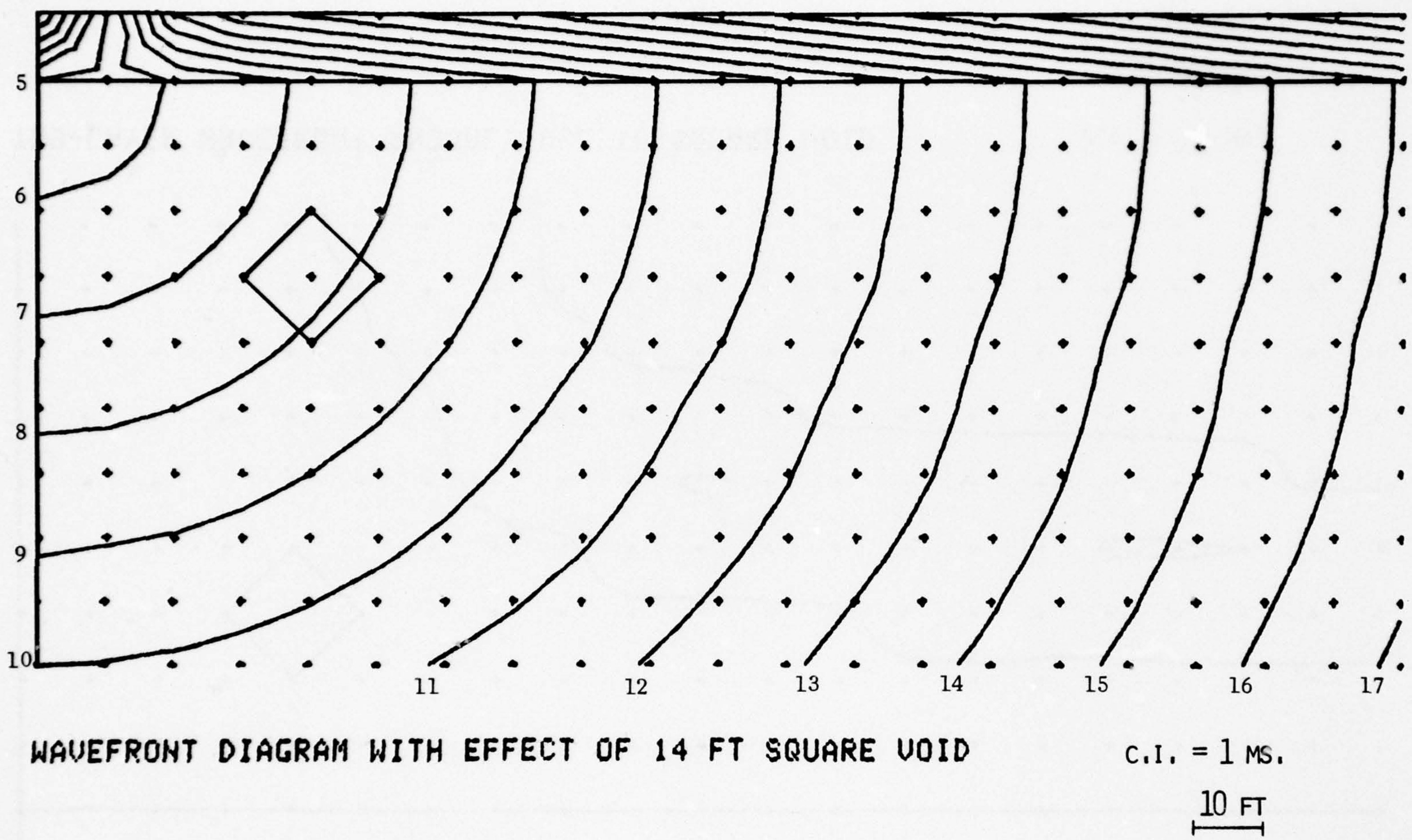


TWØ-LAYER WAVEFRONT ANOMALY DUE TO 10 FT X 60 FT VOID

C.I. = 0.1 MS.

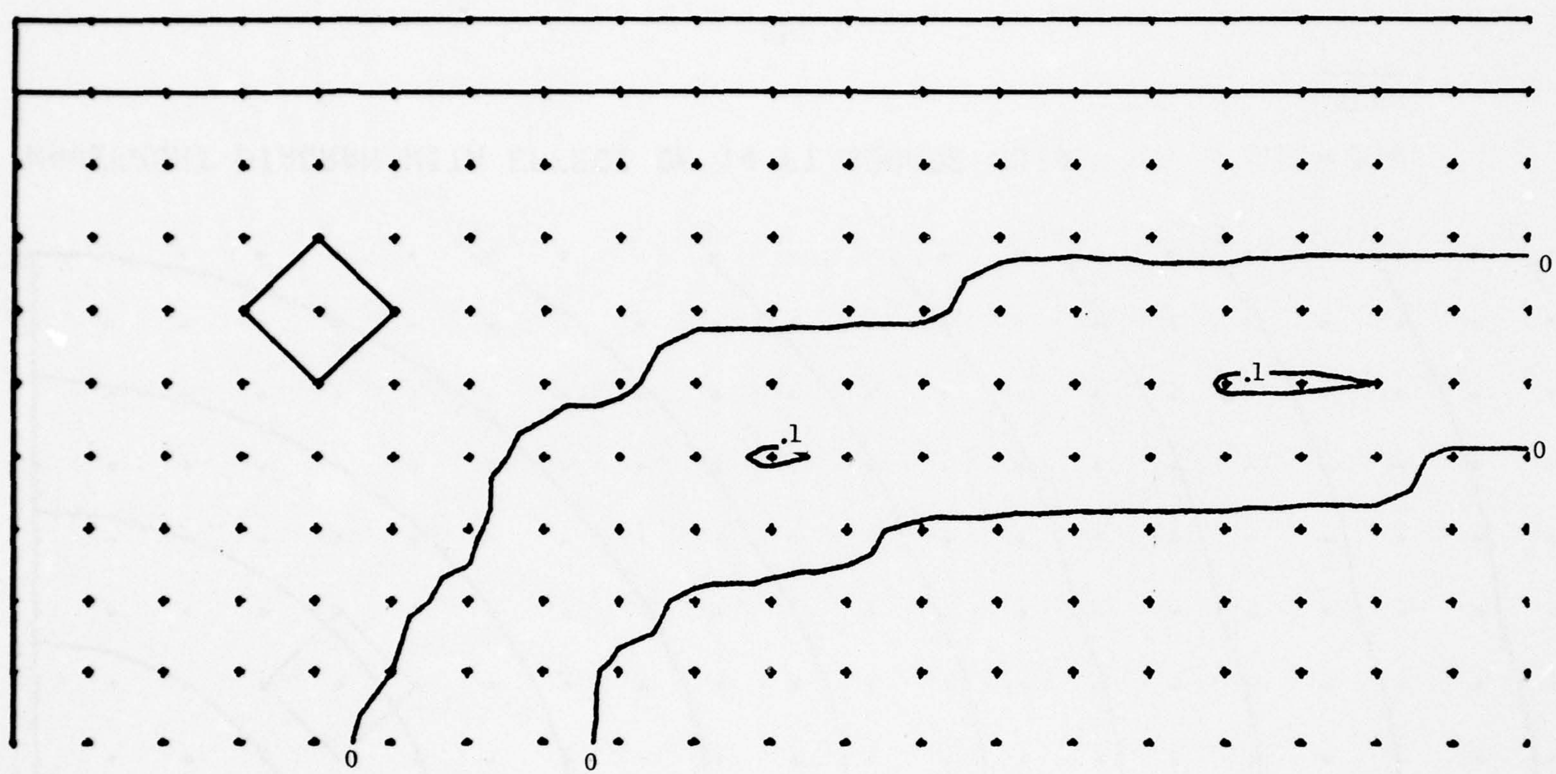
10 FT

FIG. 3



WAVEFRONT DIAGRAM WITH EFFECT OF 14 FT SQUARE VOID

FIG. 4

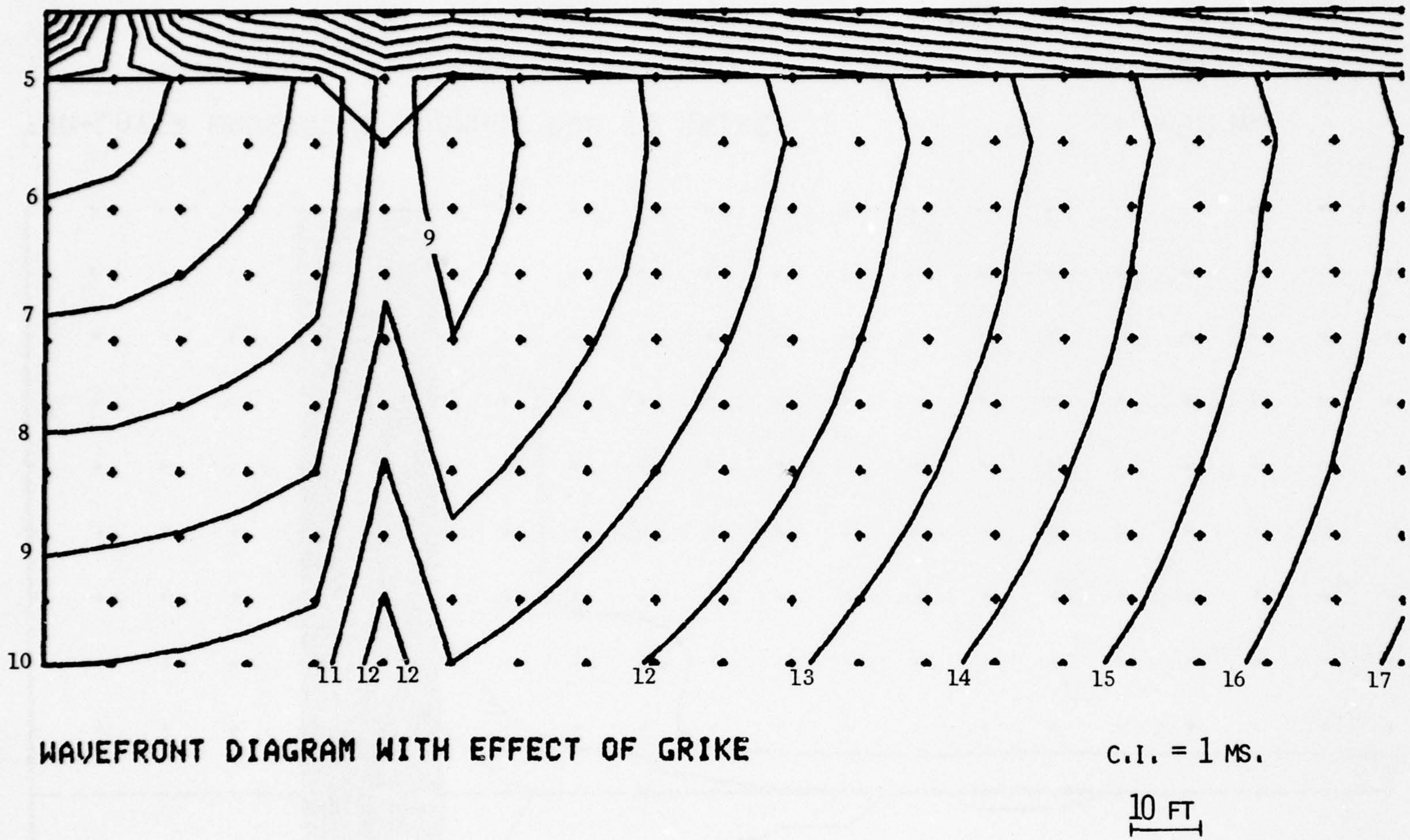


TWO-LAYER WAVEFRONT ANOMALY DUE TO SQUARE VOID

C.I. = 0.1 MS.

10 FT

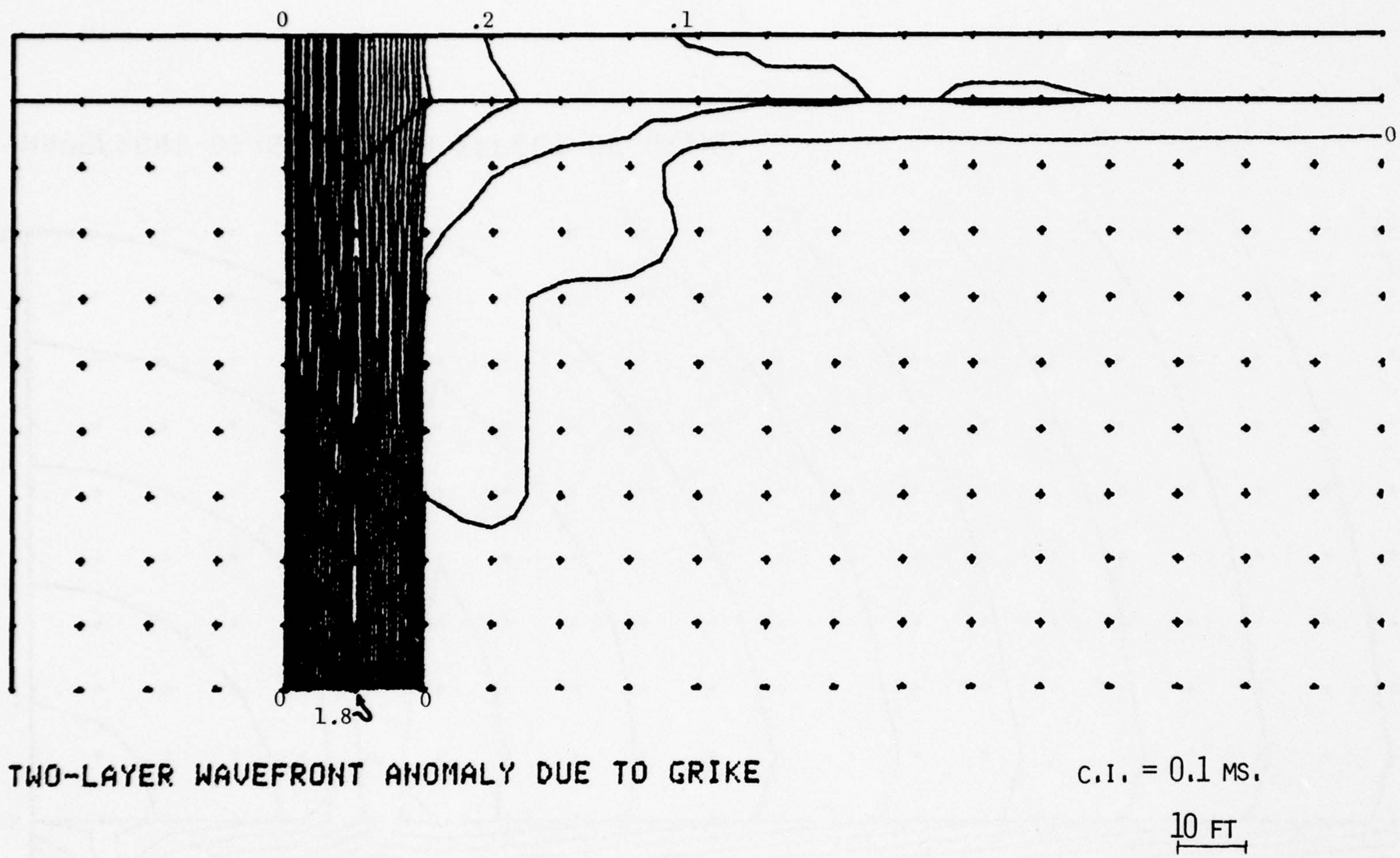
FIG. 5



WAVEFRONT DIAGRAM WITH EFFECT OF GRIKE

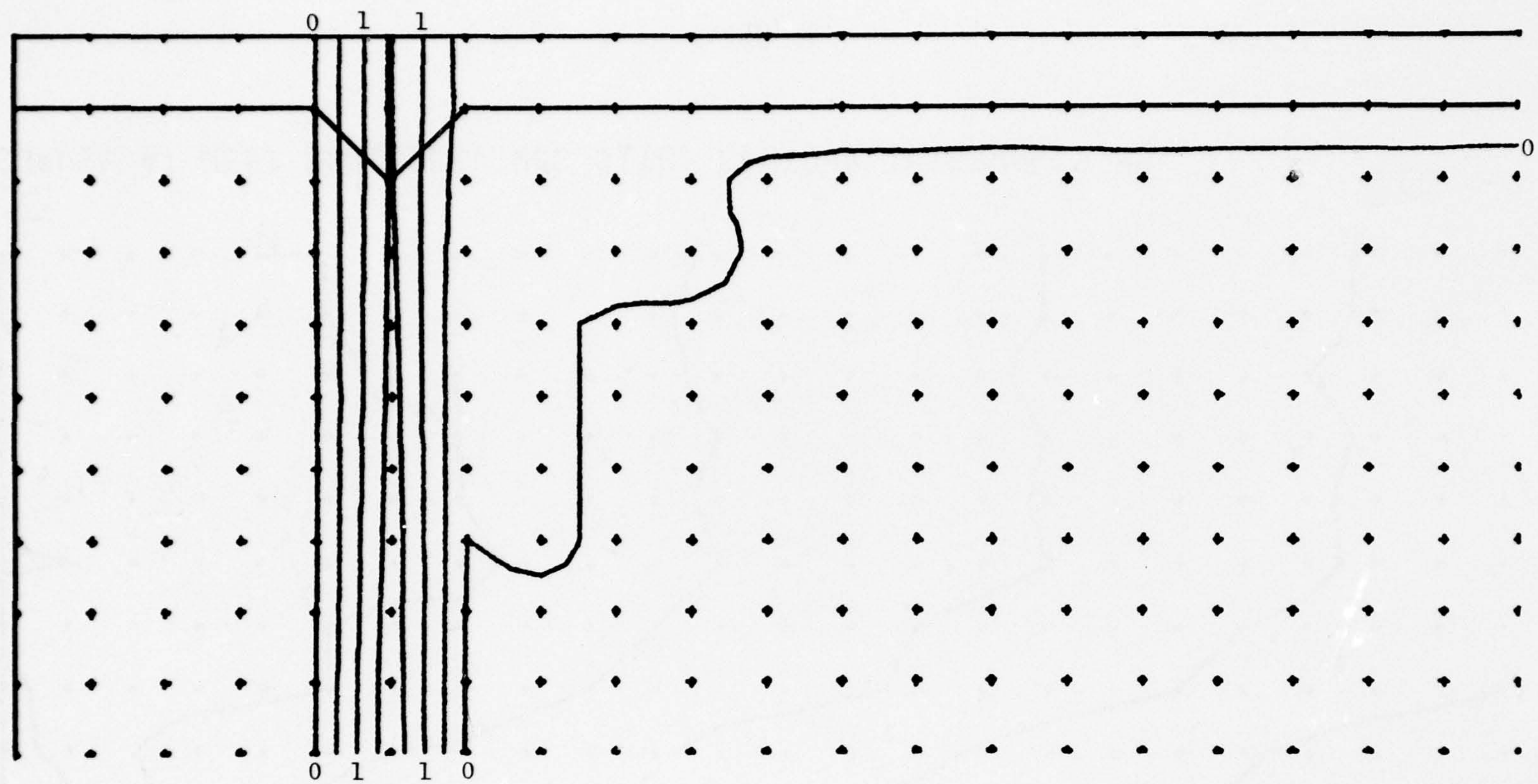
C.I. = 1 MS.

FIG. 6



TWO-LAYER WAVEFRONT ANOMALY DUE TO GRIKE

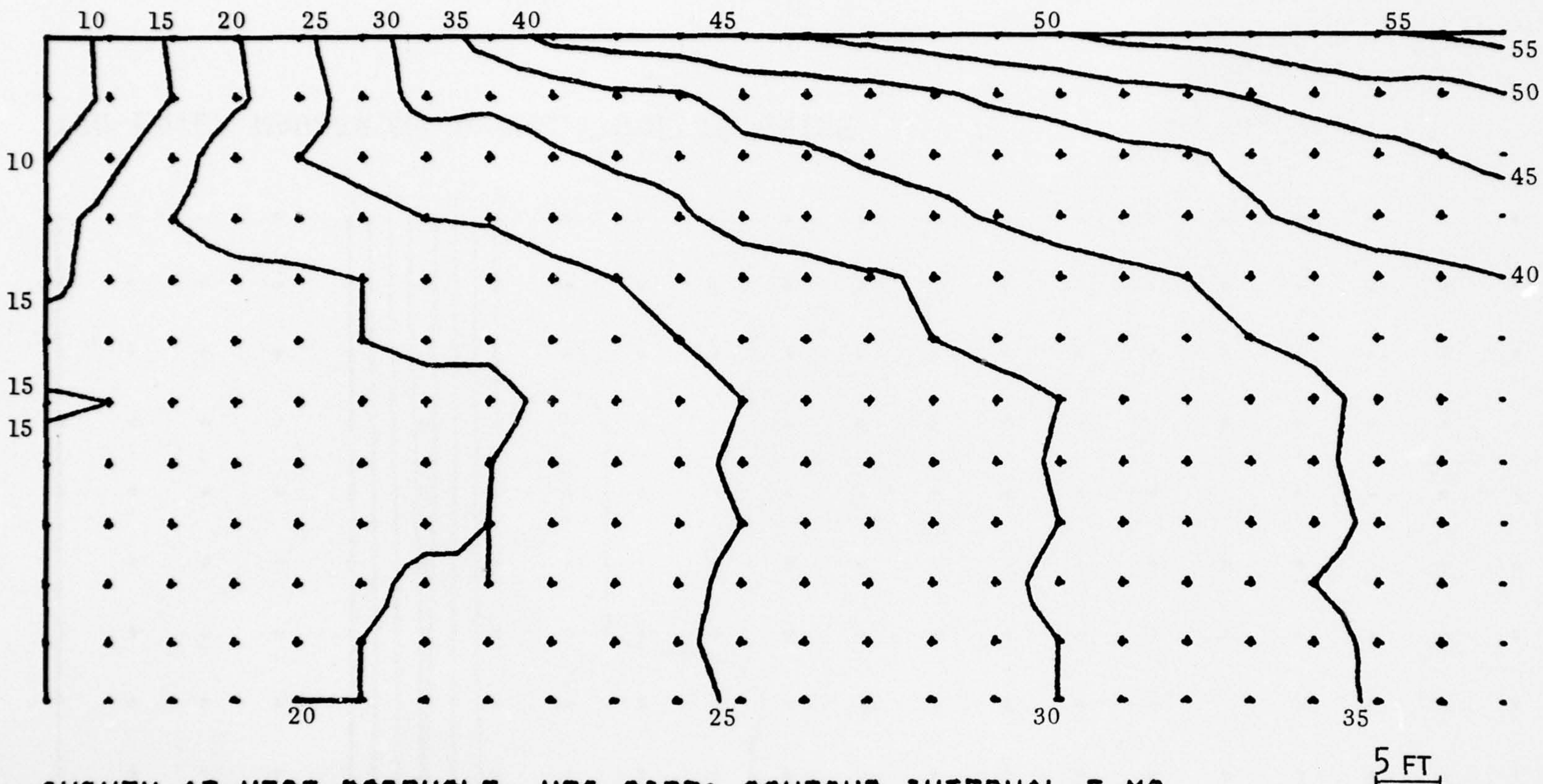
FIG. 7



TWO-LAYER WAVEFRONT ANOMALY DUE TO GRIKE

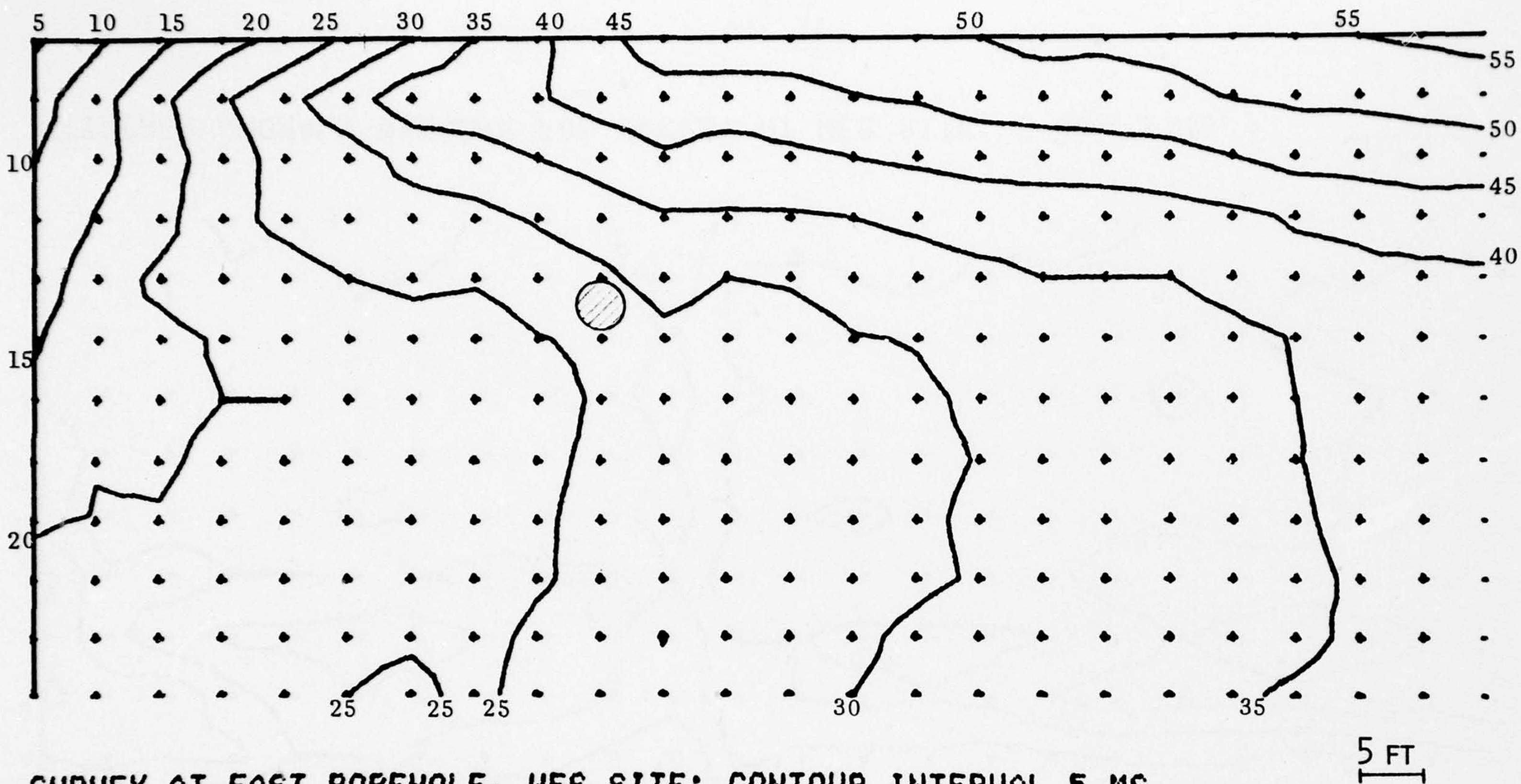
C.I. = 0.5 MS.

FIG. 8



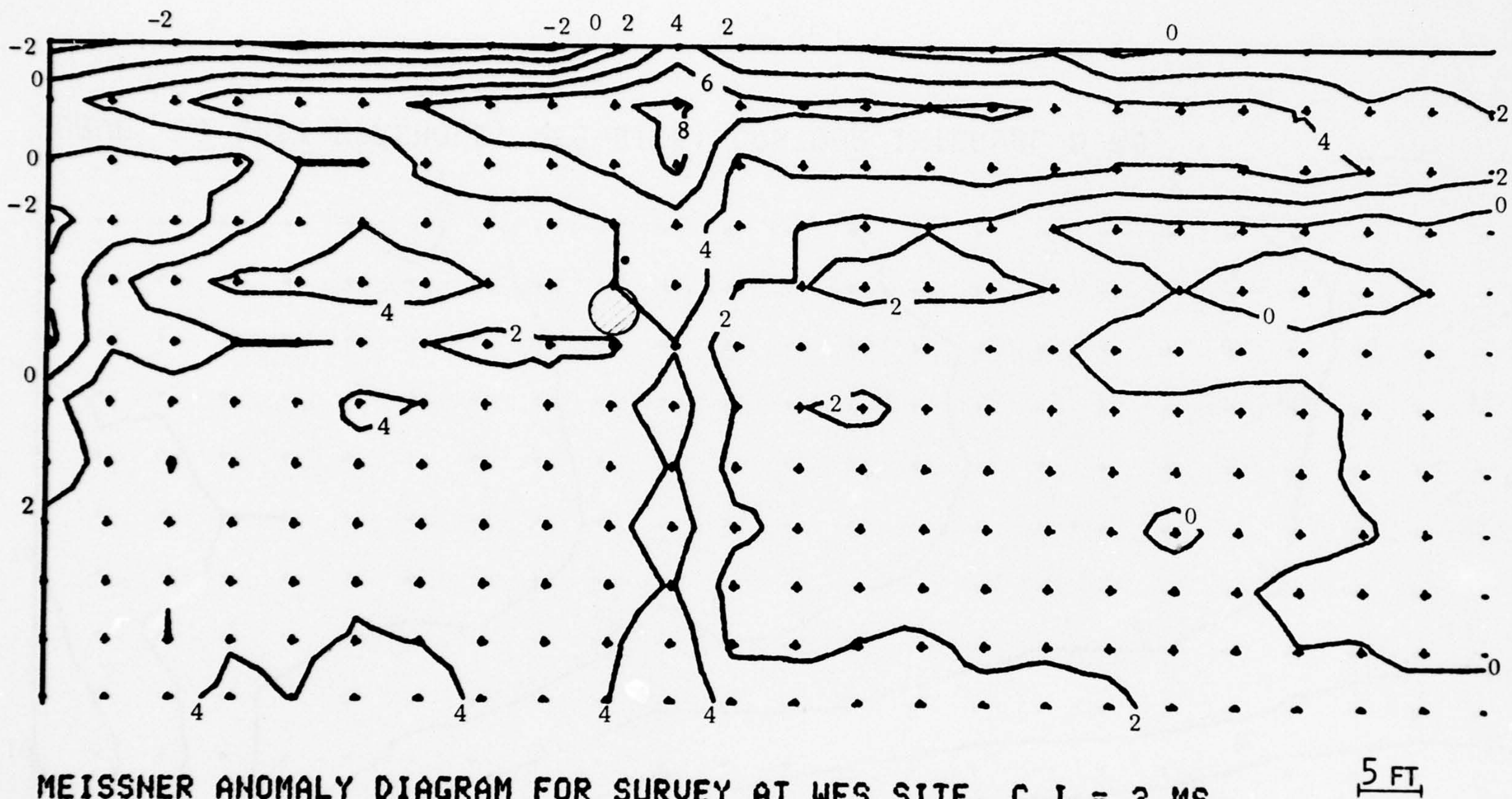
SURVEY AT WEST BOREHOLE, WES SITE; CONTOUR INTERVAL 5 MS.

FIG. 9



SURVEY AT EAST BOREHOLE, WES SITE; CONTOUR INTERVAL 5 MS.

FIG. 10



MEISSNER ANOMALY DIAGRAM FOR SURVEY AT WES SITE. C.I.= 2 MS.

FIG. 11

SEISMIC SURFACE WAVE INVESTIGATIONS OF NEAR-SURFACE CAVITIES; A COMPARISON OF FIELD RESULTS WITH FINITE-DIFFERENCE COMPUTER MODEL DATA

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THE UNIVERSITY OF MISSOURI - ROLLA

Seismograms taken in the vicinity of subterranean voids often exhibit diagnostic seismic signatures that indicate their presence. Such signatures are manifested as concave or convex phase events embedded in an exceedingly complex seismogram. These events appear to be associated with surface wave energy and represent the interference effects of the void. However, due to a total absence of theory, as applied to a void in a layered half space, it is exceedingly difficult to approach an interpretation of such events. From the data the presence of a cavity can be inferred, but an analytical approach to deciphering size, shape, depth, and content is lacking.

After five years of seismic field studies over cavities, it is concluded by this author that surface waves are the most effective probe in the detection and delineation of voids. There are four primary reasons for this conclusion:

1. Surface wave energy dominates the seismogram precisely in the record time when near surface reflections, down to depths of 3,000 feet or more, would occur.

2. Surface wave energy is confined to propagate in the shallow layers within which the cavities reside.

3. Surface waves are easy to generate.

4. The interference of surface waves with subterranean voids can readily be studied by the Finite-Difference Method of computer modelling.

Results of surface wave interference, both of the Love and Rayleigh type, by subterranean voids, as derived by computer modelling, will be discussed. Reflections of the surface wave from the leading and trailing edge of the void will be demonstrated. Dispersion and attenuation as a function of seismometer station will be discussed. Instantaneous amplitude distributions within the model section will be displayed at successive time intervals along with the corresponding synthetic seismograms.

The computer results will be compared with actual field measurements over near-surface voids. It will be shown that many of the phase patterns as derived from the computer models exist in the record section.

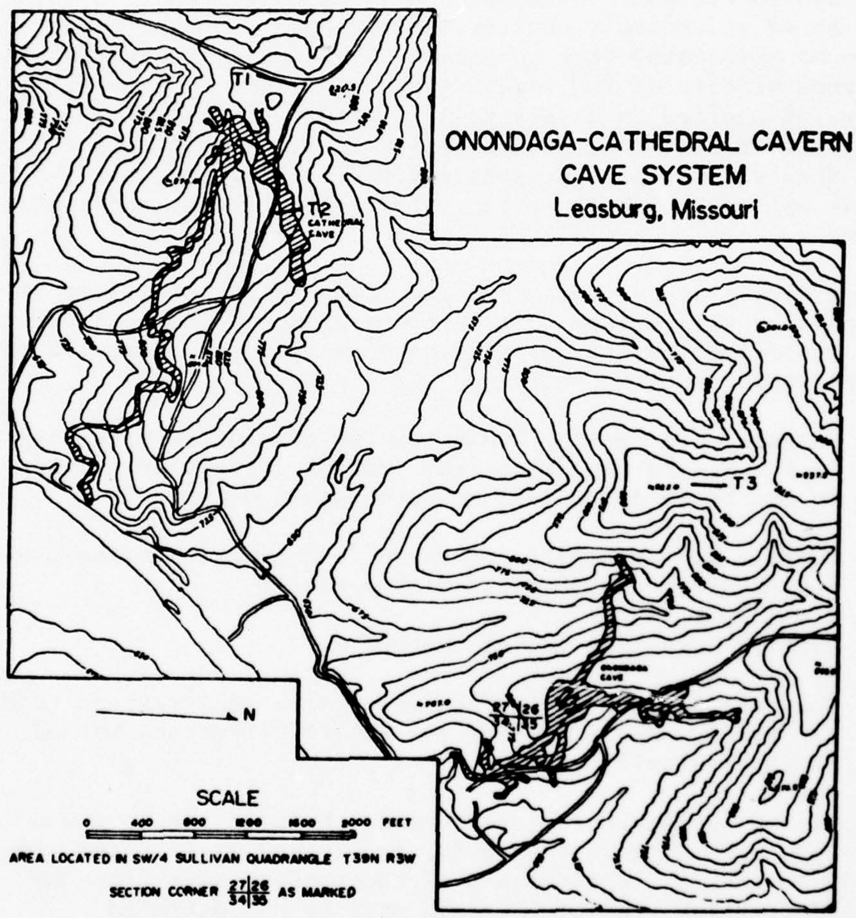
ONONDAGA-CATHEDRAL CAVERN
CAVE SYSTEM
Leasburg, Missouri
T1
T2
CATHEDRAL CAVE
T3
ONONDAGA CAVE
N
SCALE
0 400 800 1200 1600 2000 FEET
AREA LOCATED IN SW/4 SULLIVAN QUADRANGLE T39N R3W
SECTION CORNER 27|26 34|35 AS MARKED

Figure 2.

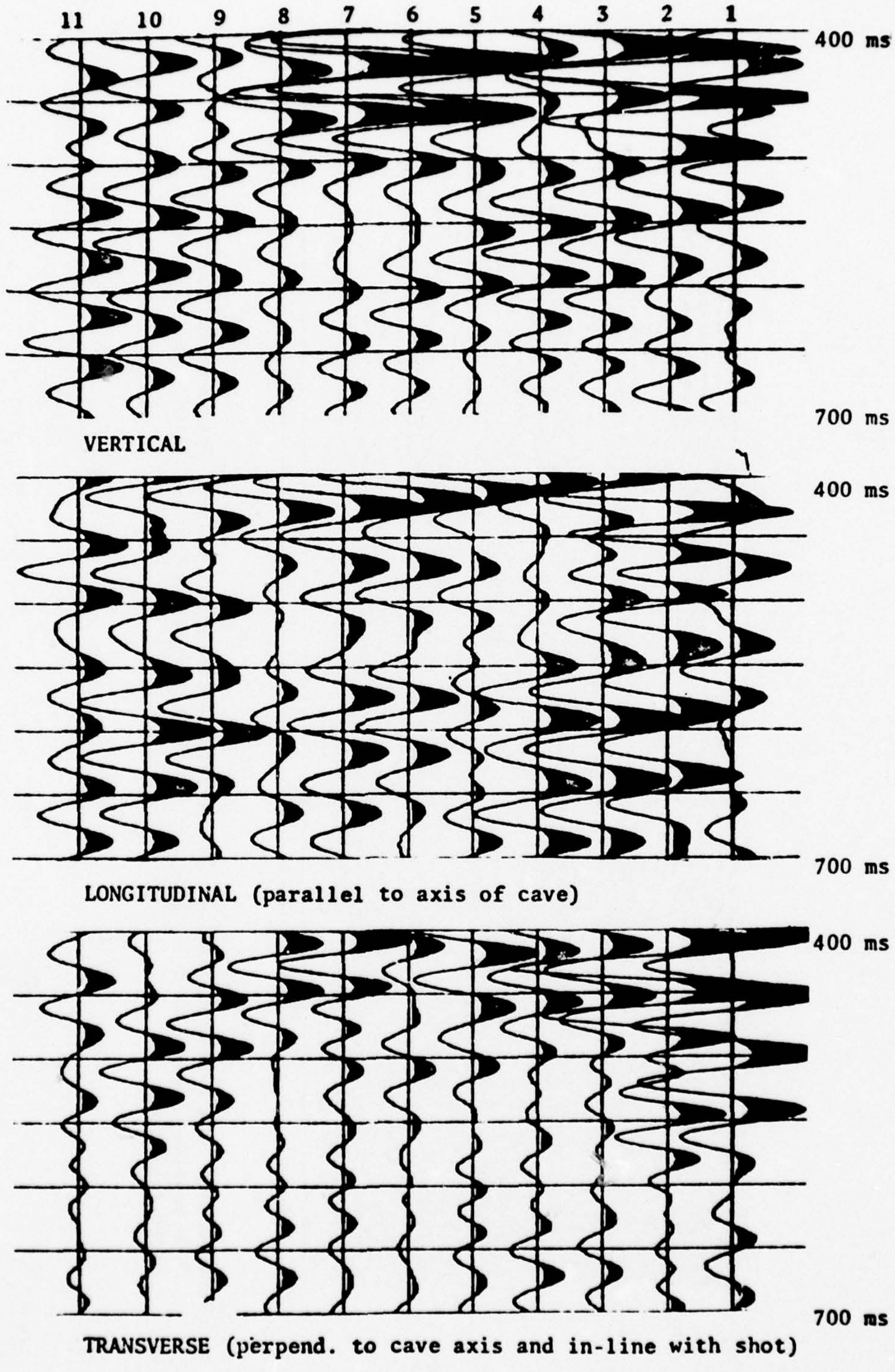

Figure 5. Three component seismographs, traverse T2, 17-35 Hertz, windowed 350-1,000 ms, spacing 10 feet, shot 50 feet to the right.

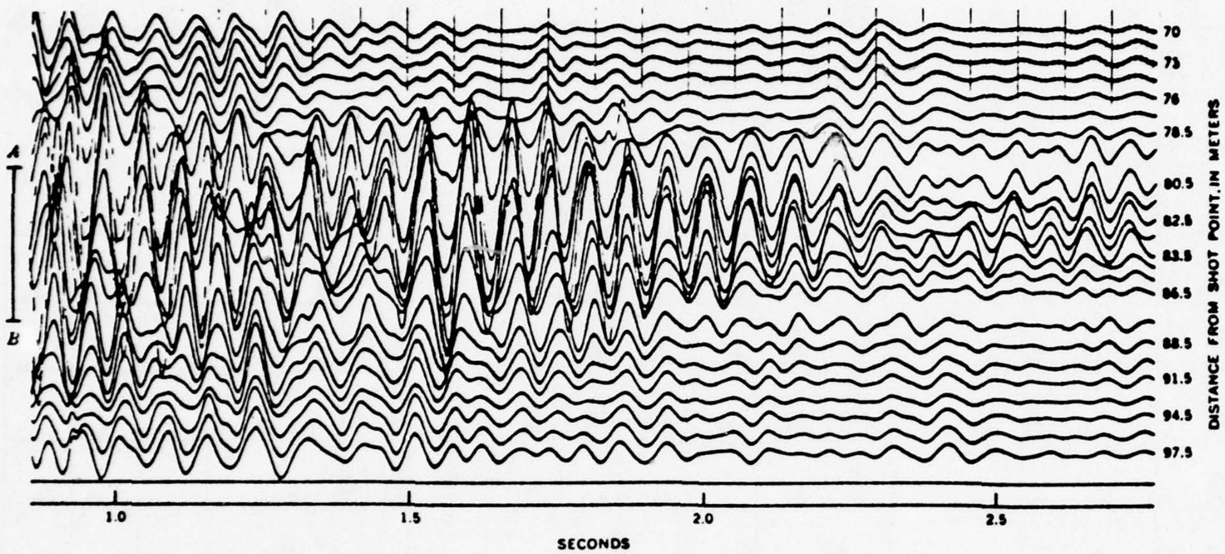

FIGURE 6.—Part of a seismogram recorded over a lava tunnel in the Pisgah lava flow, San Bernardino County, Calif. Note prominent in-phase cavity oscillations in center of seismogram. AB indicates the location and approximate width of the tunnel.

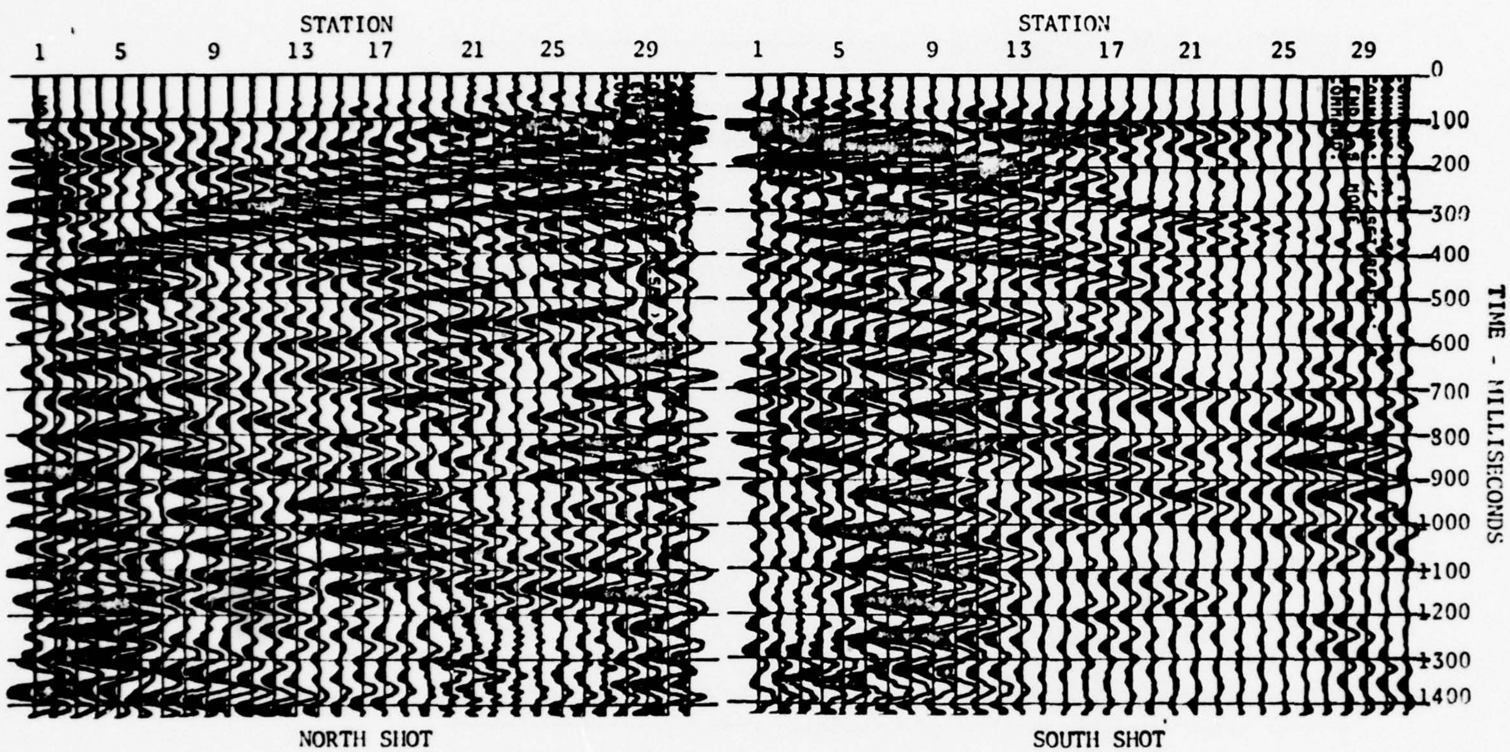

Figure 10. Forward and reverse shots along Traverse T1. Station spacing at 10 foot intervals, and the shot points are 100 feet from the end of the line.

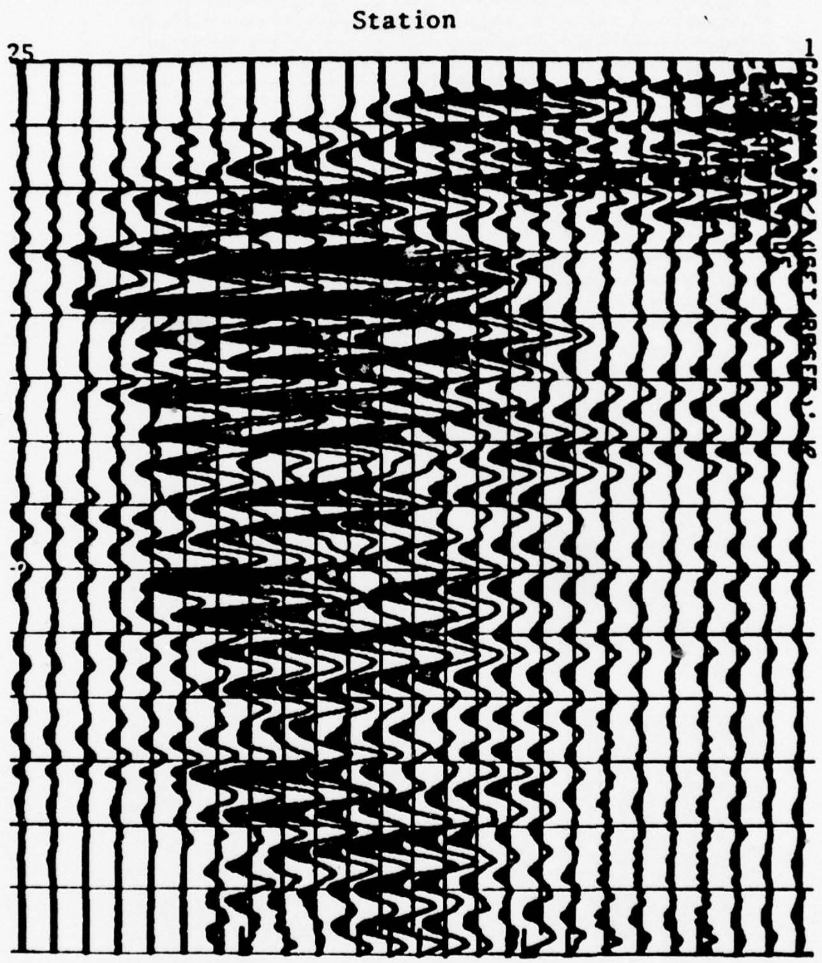

Figure 12. Seismic data over Traverse T3. Spacing 10 foot intervals. Timing interval 100 ms. Shot point 50 feet from end of line at Station 1.

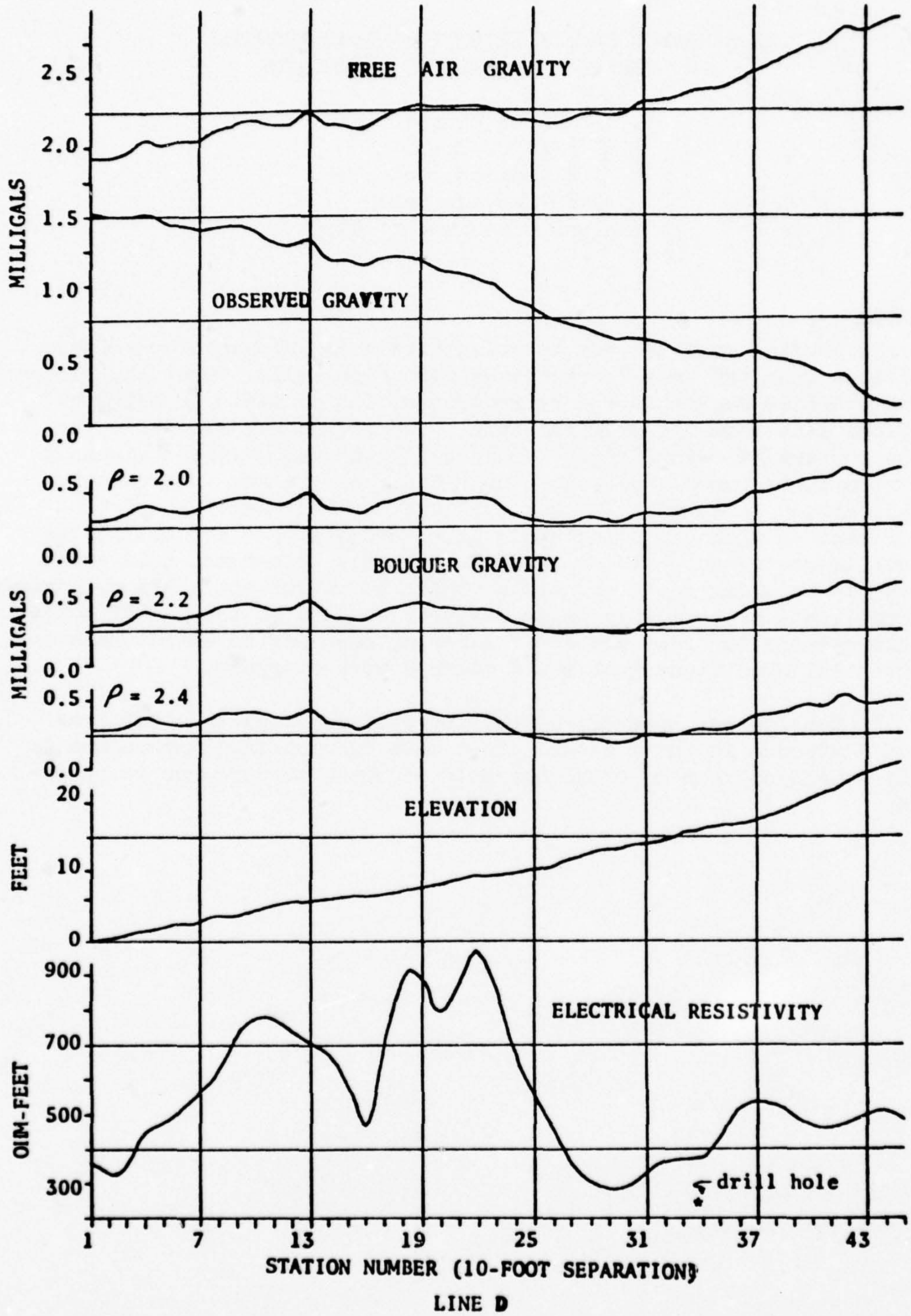

Figure 13. Gravity and Electrical Resistivity profiles for Traverse T3.

SUBSURAFCE CAVITY DETECTION USING ACOUSTIC HOLOGRAPHY AND RELATED TECHNIQUES

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Abstract

Subsurface cavities may be delineated using acoustic or seismic techniques when the data is processed holographically. That is, "images" of the cavities may be formed by reconstructing acoustic or seismic holograms made from the original data. Techniques are available for reconstructing (forming images) these holograms using lasers directly, or via computer reconstruction. The techniques are now sufficiently well-developed to suggest further applications and uses. In particular recent advances in holographic interferometry and its ability to enhance images of acoustic or seismic frequency holograms, hold great promise in bringing such techniques closer to useful application. Among such applications presently being actively pursued is the use of holographic systems to "see" ahead of tunneling machines to detect hazards or potential conditions that would cause a work stoppage.

In many cases, however, a detailed picture of earth conditions is not desired. In these cases, other more conventional approaches to cavity detection such as cross borehole acoustic surveys can be undertaken.

WES GEOPHYSICAL CAPABILITIES AND CAVITY DETECTION PROGRAM

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Vicksburg, Miss.

Abstract

Since the analysis of many foundation and soil-structure interactions requires correct in situ values for elastic moduli for foundation materials as well as a thorough knowledge of substrate conditions, the Corps of Engineers (CE) has placed a strong emphasis on the development of capabilities in the field of engineering geophysics. During the last dozen or so years, the WES has made a concerted effort to develop a capability not only meeting the primary needs of the CE, but the engineering profession as a whole. Impetus has been provided by special problems which have arisen at various Corps construction sites. The detection of subsurface solution channeling or cavities has been of primary importance in the case of large dams and reservoirs.

As a result of the ever increasing need to gain more complete information pertaining to subsurface structuring, emphasis has been placed on those techniques which would be directly applicable to Corps problems. Surface methods which have been actively pursued are various seismic techniques, acoustics, vibratory, and electrical resistivity. Subsurface methods (those which ordinarily require the use of a borehole) consist also of various forms of seismic techniques and numerous downhole logging methods. For engineering applications, it has been found that the electrical, nuclear, acoustical, and optical logging applications are most readily usable.

For several years, the Office, Chief of Engineers, has sponsored a program concerned with the improvement of geophysical methods. During the past three years, the thrust of this program has been directed toward the development of methods which might be used for the detection of subsurface cavities. In the course of this program, numerous geophysical methods have been employed in an effort to determine those most likely to provide information pertaining to the detection and delineation of subsurface cavities. Accordingly, a test site was constructed at WES which included the placement of known "cavities" consisting of PVC pipe varying in size from a 1-ft cube to a cylindrical shape 4 ft by 20 ft in length. The cavities were buried at depths ranging from 10 to 20 ft and provision was made for them to be fluid or air filled. After construction of this site, numerous geophysical techniques were employed to try to delineate the existence and shape of the known anomalies. To date, various seismic techniques such as surface refraction, reflection, cross hole, and wave-front shooting have been employed. Additionally, surface resistivity using different electrode configurations both from

the ground surface and in a newly developed focused current cross hole arrangement have been used.

Preliminary results indicate that certain methods do indeed show more promise than others. Among these are the surface electrical resistivity, cross hole seismic and resistivity, reflection, and (to some degree) wave-front methods. Future work will include the use of electromagnetics (radar), sonar devices, and possibly other techniques as yet untried at the WES test site and at other sites of known conditions. Ultimately, it will be desirable to perform tests at Karstic terrain sites and evaluate that method, or suite of methods, which would be deemed most likely to solve the problem of detection and delineation of subsurface cavities.

SURFACE GEOPHYSICAL METHODS

- SEISMIC
  1. REFRACTION
  2. REFLECTION
  3. RAYLEIGH WAVE DISPERSION
- ACOUSTICAL (LAND AND WATER SONAR)
- VIBRATORY (RAYLEIGH WAVE, STIFFNESS, AND IMPEDANCE)
- ELECTRICAL RESISTIVITY
- GRAVITY
- MAGNETIC
- ELECTRO MAGNETIC (RADAR)

SUBSURFACE GEOPHYSICAL METHODS

- SEISMIC
  1. UPHOLE/DOWNHOLE
  2. CROSSHOLE
  3. WAVE FRONT
- ELECTRICAL
  1. SPONTANEOUS POTENTIAL
  2. RESISTIVITY (CONDUCTION, FOCUSED, WALL CONTACT, INDUCTION)
     a. SINGLE POINT RESISTANCE
     b. NORMAL (POTENTIAL DIFFERENCES) ARRAYS
     c. LATERAL (POTENTIAL GRADIENT) ARRAYS
  3. FLUID RESISTIVITY
- NUCLEAR
  1. NATURAL GAMMA RADIATION
  2. GAMMA SPECTROGRAPHY
  3. GAMMA-GAMMA DENSITY
  4. NEUTRON POROSITY
  5. NEUTRON ACTIVATION
- ACOUSTICAL
  1. TELEVIEWER
  2. VELOCITY
     a. INTERVAL
     b. COMPLETE ARRIVAL RECORD (3-D)
- OPTICAL
  1. BORESCOPE
  2. PHOTOGRAPHY
  3. TELEVISION

SUBSURFACE
GEOPHYSICAL METHODS

- MISCELLANEOUS
  1. DIAMETER MEASUREMENTS
     a. MECHANICAL
     b. ACOUSTIC
  2. TEMPERATURE
  3. TRACERS
     a. INJECTION
     b. DETECTION
  4. MAGNETIC
  5. GRAVITY
  6. FLOWMETER
  7. SAMPLING
     a. SIDEWALL
     b. FLUID
  8. BOREHOLE SURVEYING

GEOPHYSICAL METHODS ASSOCIATED WITH CE CAVITY DETECTION PROGRAMS

METHOD	STATUS	DEGREE OF SUCCESS
SEISMIC		
1. REFRACTION	TRIED	MARGINAL
2. REFLECTION	TRIED	MARGINAL
3. WAVE FRONT	TRIED	MARGINAL
4. CROSSHOLE	TRIED	BETTER THAN MARGINAL
RESISTIVITY		
1. SURFACE	TRIED	BETTER THAN MARGINAL
2. CROSSHOLE	TRIED	BETTER THAN MARGINAL
RADAR	IN USE NOW	
ACOUSTICS (INCL. SONAR)	NOT TRIED	
MICROGRAVITY	NOT TRIED	

OVERVIEW OF ELECTROMAGNETIC METHODS IN GEOPHYSICS AND APPLICATION OF RADAR TO THE DETECTION OF CAVITIES IN SALT

R. R. Unterberger
Texas A&M University

Abstract

Radio and radar wave propagation through the earth is reviewed briefly starting with the first publication in 1910. Researchers in this field appear to have difficulty in convincing people that radio waves can penetrate at least some earth materials. Some of this unbelief lingers even today. A short motion picture of a radar data display "seeing" through 450 ft of salt will be shown. The use of an FM-CW radar system modified to probe through rocks is described. The 4300 MHz system is swept linearly at 120-Hz rate over 60 MHz. The reflected microwave swept frequency signal is mixed with a representative sample of the transmitted wave and an audio beat frequency results which is analyzed for its Fourier components. Knowing the system parameters of the radar and a speed of the microwaves through the rock ($\approx$400 ft/μs in salt), ranges to one or more discontinuities in the rock are determined. The salt-air interface roof of a tunnel in salt is mapped by radar profiling through 14 to 36 ft of Grand Saline Salt Mine salt in Texas. Other microwave probing results by this system in salt mines in Pugwash, Nova Scotia, and Goderich, Ontario, Canada, show salt-dolomite and salt-anhydrite contact detection capabilities and ranging in salt to 80 feet.

DETECTION OF SUBSURFACE CAVITIES
BY GROUND PROBING RADAR

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Geophysical Survey Systems, Inc.
Hudson, New Hampshire

INTRODUCTION

Subsurface cavities can be detected using specially designed radar equipment under certain conditions. This presentation will describe a comercially available state-of-the-art system developed and manufactured by Geophysical Survey Systems, Inc. and a variety of applications to which it has been applied relative to the detection of subsurface cavities.

The time allocated for this presentation limits the number of case histories that can be presented and the amount of detail that can be discussed. However, it is hoped that the samples selected will demonstrate the capability of the GSSI radar equipment in helping to solve cavity detection problems.

The information presented today will not include theoretical considerations and mathematical formula relative to the technology of subsurface radar. This type of material, along with a list of references, is available on request. I will also not use this precious time discussing various engineering and military problems that require the detection of subsurface cavities, what causes them - and what should be done when they are found. These matters are the concern and responsibility of experts in the fields of engineering, geology, and military operations.

The case histories presented will adhere to the WES definition of the term "subsurface cavity" (see page 127).

There are other kinds of cavities that will not be discussed here however, when we look into this subject we realize that the detection of this kind of cavity occupies more time and effort than the search for all other kinds of cavities.

Note: The slides used in this presentation are not available for publication.

SYSTEM OPERATION

This block diagram illustrates the basic operating principles of the GSSI radar. The power supply furnishes a regulated DC voltage to the impulse transmitter which is triggered to fire at a 50 KHZ repetition rate. The impulse transmitter generates a base band voltage pulse of only a few nanoseconds in time duration. The radiated signal is a very short electromagnetic transient having a wide bandwidth of more than 100 megahertz, in the VHF range. Reflected signals from various interfaces are received by the antenna during the transmitter off-period. The receiver electronics amplifies the received reflections and translates the high frequency data to audio frequencies using the time domain sampling technique.

As the transducer is moved alongthe route being surveyed, the time of flight of reflected signals will vary proportional to the depth of the varying geological interfaces.

The continuously acquired data is recorded on both a magnetic tape recorder and a graphic recorder. The tape recorder is used in order to acquire data at the fastest possible rate since the printing speed of the intensity-modulated graphic recorder is limited. The recorded data can later be played back at a lower tape speed compatible with the graphic recorder speed capability. Because the data is on tape, it can be processed further when necessary.

The transmitter output pulse is mono-cycle (single polarity) with some overshoot.

While the pulse launched from the antenna radiating element is sinusoidal due to the filtering effect of the finite bandwidth antenna. The reflected wavelets are similar in appearance.

The graphic recorder is an electrostatic intensity modulated device that utilizes a stylus that travels across the width of the paper and is synchronized with the impulse transmitter trigger so that one graphic recorder scan represents one sampled radar scan. Signals indicated in red, whose amplitudes are above a preset threshold level, are printed as black or shades of gray proportional to signal amplitude. The weaker signals, below the threshold, are indicated as white on the record. As the chart paper advances, successive scans are printed side-by-side very closely. This continuing process produces the graphic profile record.

SYSTEM MODULES

This is one of the GSSI Subsurface Interface Radar Systems currently in production, referred to as a SIR SYSTEM.

The SIR SYSTEM-7 consists of the following modular units, the Radar Control Unit, a Transducer, the Tape Recorder, the Graphic Recorder, a DC Power Distribution Unit, an AC Power Supply, a Remote Control Unit, a Transducer Control Cable, and module interconnect cables. SIR SYSTEMS can be powered from AC or DC sources.

The system is designed to accept various transducers that vary in mechanical construction and electrical characteristics. The selection of the transducer is dictated by the survey requirements. If high resolution, near-surface data is required, a small high frequency transducer is selected. Or, if the problem requires deep probing, a large lower frequency transducer can be used.

The Model 3055 Transducer is a general purpose unit constructed with built-in wheels that allows it to be easily used for surface scanning. The half amplitude pulse width is approximately 3 nanoseconds and the center frequency is approximately 125 Megahertz.

The Model 3110 has the same electrical characteristics but is packaged in a light-weight fiberglass case to allow it to be used easily for wall and ceiling probing in mines, tunnels or caves.

The Model 3103 Transducers are operated in pairs, the bistatic mode, one unit being the transmitter and the other the receiver. These relatively small units have a pulse width of approximately 1½ nanoseconds with a center frequency of about 400 megahertz.

The Model 101B is the smallest transducer in production at GSSI and its transmitted pulse has a rise-time of approximately 300 picoseconds, with a center frequency of about 900 megahertz.

The Model H6/110TR Borehole Transducer was designed for borehole logging in 3 inch holes. Pulse width of this unit is approximately 2½ nanoseconds and its center frequency is about 300 megahertz.

When used with the H6/110T Transducer which is a transmit only unit, the pair can be used for probing from hole to hole, cross borehole probing.

The Model 4700 Radar Control Unit is the heart of the GSSI radar system and allows the operator to adjust various ranges, signal amplitudes, time gain amplification, filtering, scan speeds, etc. The unit also contains a cathode ray tube monitor that displays the received radar scan waveform. This can be monitored at the transducer output - the putput of the control unit, or the output of the tape recorder.

VARIOUS APPLICATIONS

The following group of slides illustrate the various locations and applications for which the GSSI radar has been used to detect subsurface cavities. Sample data acquired at some of these sites will be presented later.

Here the system is being used in Saudi Arabia for mapping the location of unknown buried pipes prior to construction of a sewerage system.

While one of the natives studies the intricacies of the radar control unit.

The equipment has been used along the Alaskan Pipeline in order to detect ice filled cavities in the permafrost.

The transducers used were operated in a combination monstatic (one unit, both transmitting and receiving)and bistatic modes. (one unit transmitting the other unit receiving)

Here a pair of Model 3112 Transducers are being used in the Canadian Northwest Territory.

And in Alaska, a pair of transducers was mounted on a helicopter for Ice thickness profiling and this configuration was also used for frazil ice detection.

Near this area in Florida the GSSI radar was used to detect sub-surface cavities.

Here a high resolution transducer is being used to probe the rib thickness between cavities at a high wall coal mining operation.

The transducer can be articulated on the test cart to probe through the ceiling, floor or walls of the hole.

DATA FROM VARIOUS SURVEYS

This data was taken in a Canadian Northwest Territories clearly indicating some styrofoam sheets that were buried about 3 feet under a frozen road.

Interfaces of differnet geological materials are shown here.

This is the site at Reddick, Florida where the following data was taken at the Medford Cave.

Target indicated on Column 16 location 16, clearly shows the presence of a subsurface cavity ($\approx$ 9 ft. deep) and on Column 17, location 23, another cavity is indicated ($\approx$ 12 ft. deep).

These two scans, row 23 and row 24 were taken parallel to each other and indicate targets at column 16 to 17½ and at column 15

Two scans diagonal to the survey grid were taken over the cavity, the lower scan was taken parallel but off to one side. The data indicates that the cavity is relatively long and that the upper scan is closer to being directly over it than the lower one.

Here vertical piping is shown exposed at a quarry in Florida.

This is data taken at another area prevalent with vertical piping. The inverted hyperbolas represent the hole targets.

At the 60' station a tunnel at a depth of approximately 4 feet and about 6' wide is clearly indicated. The tunnel walls are indicated by the interruptions of the geological interface.

This data was acquired by scanning along a highway in the Northwest Territories. In this particular area a stream bed has been filled in to make the highway grade level and two culverts were buried under the stream bed to allow water flow, which are clearly indicated.

This data was also taken along a highway. This road, however, was paved and located in Rockport, Mass. The major target near the center of the data is a large air-filled cavity under a dry granite bridge.

This data illustrates the classical vertical hyperbolic shaped targets as acquired by radar when scanning across pipes.

LIMITATIONS

The high frequency electrical characteristics of the material being probed by electromagnetic impulse radar vary greatly in different locations and in adjacent geological layers. The conductivity of the material effects the depth of penetration of the radar pulse. In general, the lower the conductivity, the deeper the penetration. The strength of the reflected signal is stronger when the dielectric constant ratio or dielectric contrast is high, the frequency content of the radiated pulse also dtermines the depth of penetration and the resolution of the received data.

IN CONCLUSION

It has been shownby the various samples presented that a rapid, non-destructive procedure for detecting subsurface cavities has been developed, and that the instrumentation used to perform this procedure is commercially available, easy to operate, portable, operates on very low power and provides its user with high resolution, graphic records, showing the size, location, and depth of subsurface cavities.

WES Definition of subsurface cavity

"The term "subsurface cavity" is broadly interpreted to mean any void or pocket (air or fluid filled or filled with some secondary geologic material) in soil or rock which may or may not have surface expression. Cavities may be geological in origin (i.e., formed by solution processes in limestones and dolomites or by tectonic activity in any type rock) or manmade (such as buried pipes, tunnels, mines, etc.) and may vary in dimensions form a few centimeters to hundreds of meters."

Cross-Borehole Probing for the Detection of Anomalies*

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Abstract

Is it possible to know what exists beneath the ground before you dig it up? With the electrical methods for probing subsurface electrical structures being developed and tested at LLL, the answer is yes. Our approach has been to adapt the data-collection and -interpretation procedures that are being applied in medical diagnostics (e.g., brain and whole-body scans) to probing the rough with radio waves. We map the region of interest with electrical signals transmitted between transmitter and receiver pairs lowered in boreholes on opposite sides of the region. The signals so produced vary according to the electrical properties of the media through which they pass; from their signature we can reconstruct the subsurface structure, identifying anomalies, water-bearing strata, sand lenses, and the like.

Early experiments have led to radio-wave probing techniques with good resolution when the subsurface region is relatively homogeneous and the electrical constrast between the host medium and the anomaly of interest is small. Probe separations can be from 30 m to 1 km, depending on the media involved. We have used these techniques, for example, to determine the fracturing pattern induced in a coal seam by detonating high explosives. The dominant propagation mechanism from transmitter to receiver through this fractured coal medium is easily and adequately described by straight-line ray optics.

More recently, we extended our studies to include locating high-contrast anomalies in the host medium, i.e., anomalies with significantly different electrical propagation characteristics from the host medium. In two experiments we used high-frequency electromagnetic waves propagated between boreholes to locate a tunnel in granite. In these experiments, we found the dominant interaction mechanism to be an oscillating signal with deep minima near the tunnel. These signal minima were centered about the projected middle of the tunnel, which suggested a useful diagnostic: the two strongest adjacent minima define the most probable sector containing the tunnel. Simultaneously lowering a transmitter and receiver held at equal depths provides a horizontal view of the anomaly. Other views are obtained by lowering a transmitter and receiver offset by a fixed distance. By recording data at a number of depths in the borehole, drawing sectors from their minima, and then superimposing these sectors (or views) as in medical back-projection, we could estimate the tunnel's location.

*This work was performed under the auspices of the U.S. Energy Research and Development Administration under contract number W-7405-ENG-48.

The excitation frequency in Figure 2 was 57 MHz. The effect of varying f frequency was most evident in the width between successive maxima and minima. Going to high frequencies gives better detail, but lower frequency signals propagate farther. Below about 20 MHz, we found that signal variation was generally insufficient to allow confident interpretation of a tunnel's location in the presence of small-scale geologic noise. Between 25 and 60 MHz, resolution was adequate. Above 60 MHz, the data varied too rapidly for successful analysis with the simple data-interpretation method.

Acknowledgment

The experimental work described herein was supported by the Defense Advanced Research Projects Agency and the data interpretation development was supported by the Department of Transportation.

DETECTION OF SUBSURFACE CAVITIES BY SURFACE REMOTE SENSING TECHNIQUES

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Both natural and man-made underground cavities and tunnels have been remotely detected from the surface using a special ground penetrating radar, by gravity measurements, and by earth resistivity profiling. Verification tests showed that gravity measurements located large cavernous areas but did not detect mud-filled troughs; radar detected air-filled cavities at maximum depths of 4.6 meters at one site, but could not resolve 0.6-meter diameter vertical cylindrical cavities at another. Earth resistivity measurements using a pole-dipole electrode arrangement located cavities at several sites, indicating targets at depths greater than 30 meters. Both air-filled cavities, including vertical cylinders, and mud-filled troughs were detected using the resistivity technique, giving accurate depth and size resolution. A large mud-filled trough was detected at a 9.1-meter depth that extended below 30.5 meters. Mine passages in granite with cross sections of 2 x 2 meters were detected at depths ranging from 9 to 30 meters. Greater tunnel detection depths were realized at foreign sites for tunnels with the same approximate dimensions.

An automatic field data acquisition system was designed to speed up the field data collection process and to improve the data accuracy through digital recording. Data reduction and interpretation was improved by use of an interactive computer system. The earth resistivity survey system and its military applications will be illustrated and described.

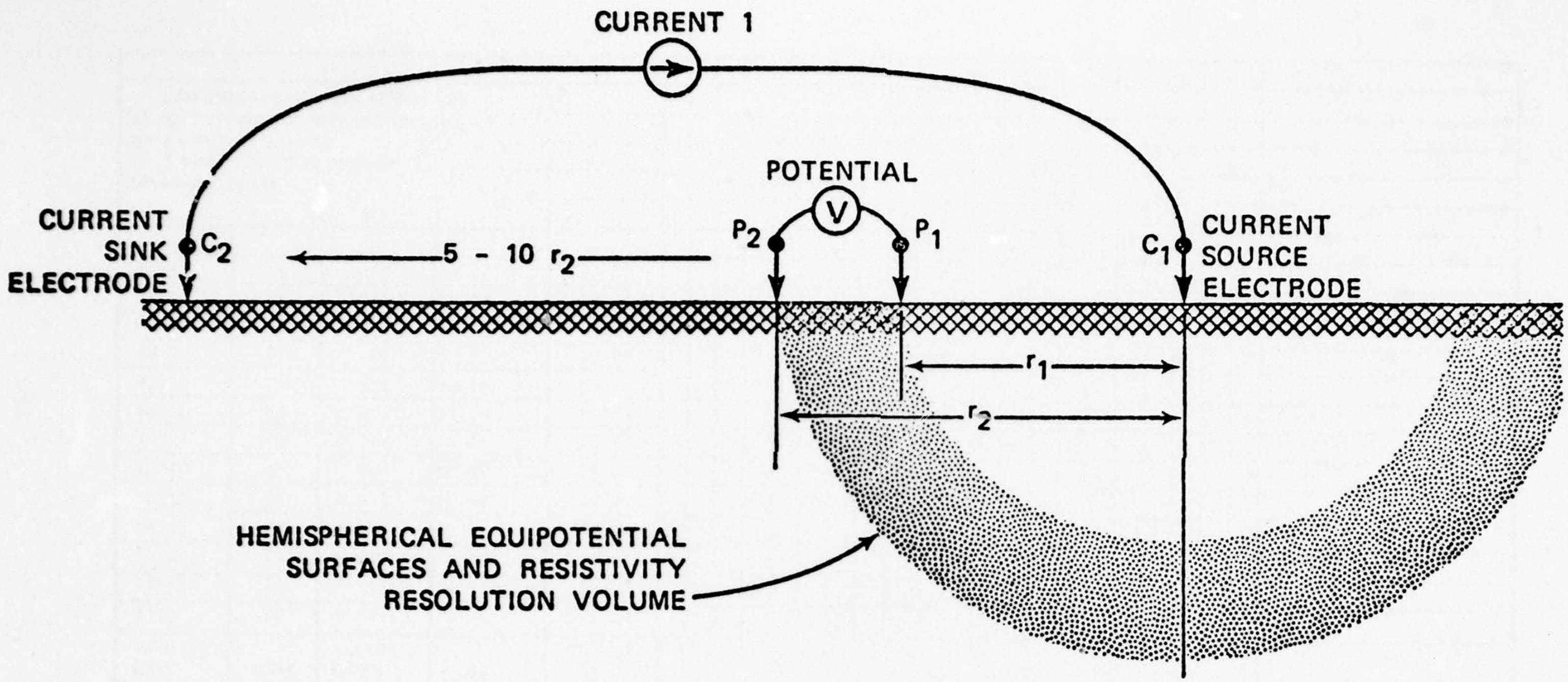


FIGURE 1
POLE-DIPOLE EARTH RESISTIVITY ELECTRODE ARRAY

PROJECT 14-4250

TEST NO. 2

DATE 17 June 1975

WEATHER CONDITIONS Cloudy-Cool, About 50°

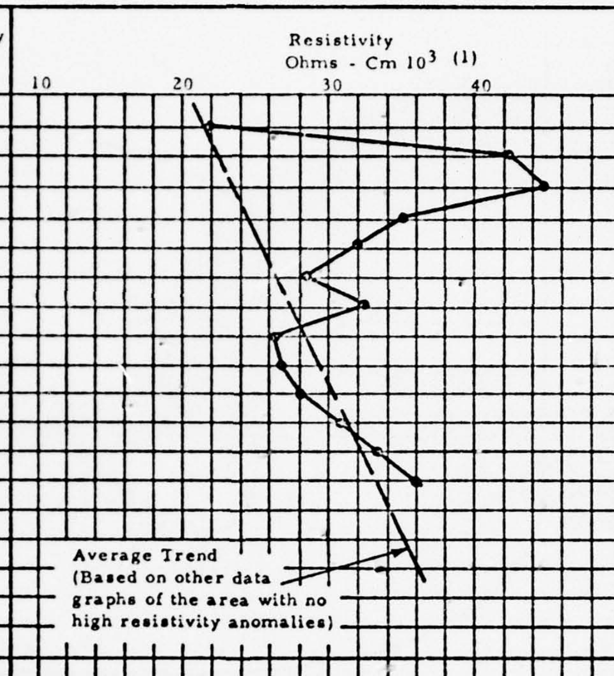
SITE Colorado School of Mines

AREA Service Road Crossing Adit

CURRENT PROBE POSITIONS 000-600; 000 + 10

OBSERVER F & H

P-P[2] Feet Pos. [3]	D Feet	Reading Ohms or Volts	Factor 10^3	Resistivity Ohm Cm x 10^3	Interpretation
5-15	10	0.605	1.44	21.78	
10-20	15	0.411	3.83	42.23	
15-25	20	0.250	7.18	44.88	High-Outcropping
20-30	25	0.122	11.49	35.04	High-Outcropping
25-35	30	0.077	16.75	32.33	
30-40	35	0.050	22.98	28.50	
35-45	40	0.043	30.15	32.41	High-Mine
40-50	45	0.027	38.30	26.24	Low
45-55	50	0.023	47.38	26.77	
50-60	55	0.020	57.45	28.00	
55-65	60	0.018	68.43	31.31	
60-70	65	0.017	80.43	33.58	
65-75	70	0.016	93.31	36.08	High-Rock



Current = 40 ma

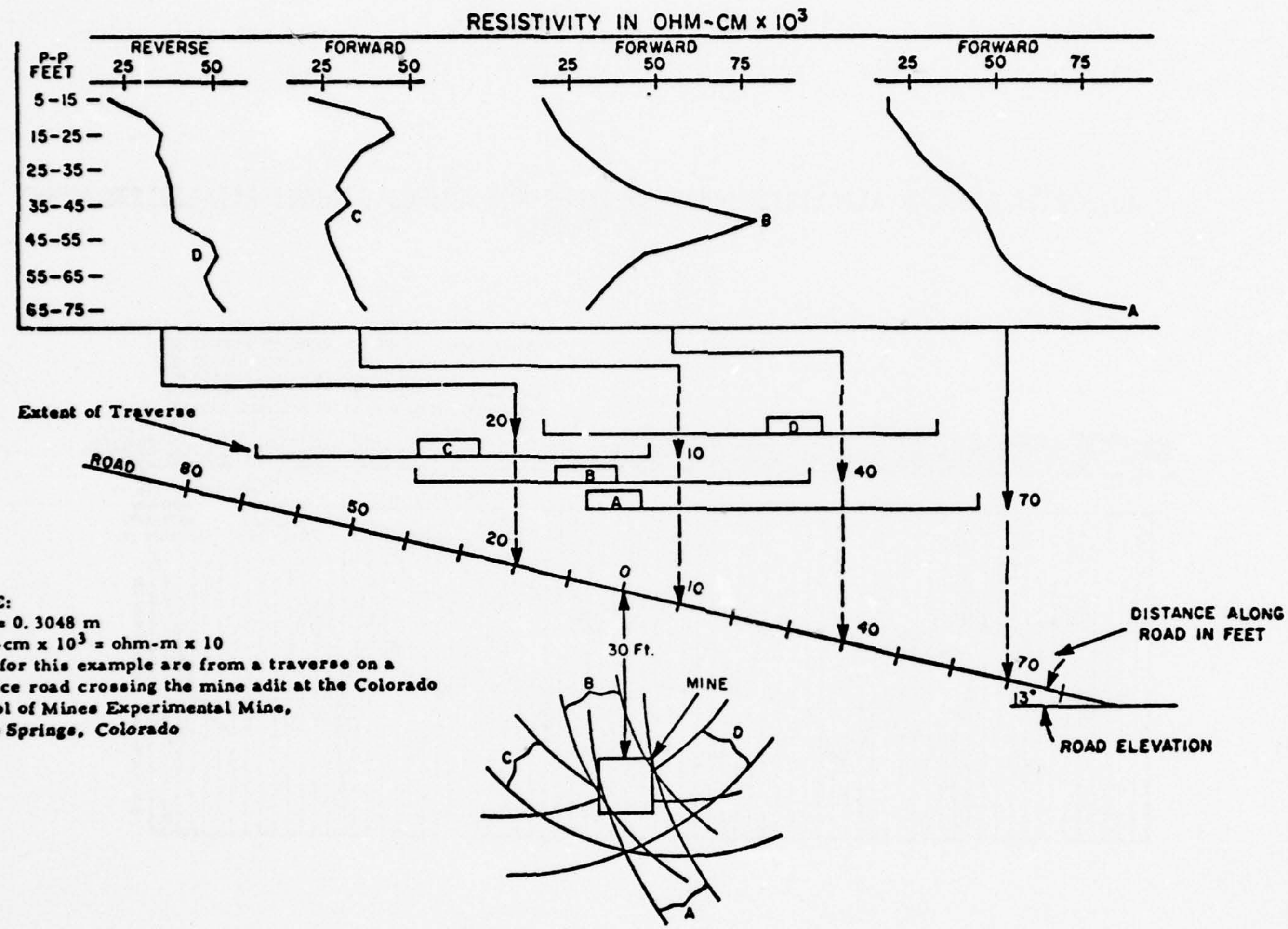
(1) 1 ohm - cm = 10 ohm-m

(2) 1 foot = 0.3048 m

(3) Pos. indicates measurements on a line between current electrodes

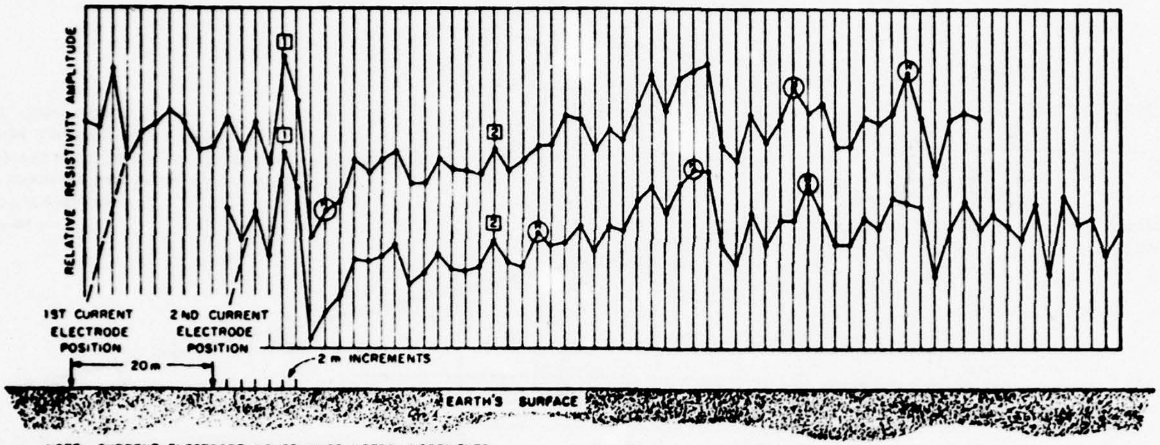
FIGURE 2

SAMPLE RESISTIVITY TRAVERSE DATA SHEET WITH ANOMALIES MARKED



NOTE:
1 Ft = 0.3048 m
Ohm-cm x 10^3 = ohm-m x 10
Data for this example are from a traverse on a service road crossing the mine adit at the Colorado School of Mines Experimental Mine, Idaho Springs, Colorado

FIGURE 3
EXAMPLE SHOWING GRAPHICAL METHOD OF LOCATING A RESISTIVITY ANOMALY



NOTE: CURRENT ELECTRODE MOVED IN 20-METER INCREMENTS.
POTENTIAL ELECTRODES SPACED 2 METERS APART AND INCREMENTED IN 2-METER INCREMENTS.
Ⓗ MARKS RESISTIVITY "HIGH"
1 EXAMPLE OF "HIGHS" CAUSED BY SURFACE EFFECTS.

FIGURE 4
EARTH RESISTIVITY PROFILE COMPARISON SHOWING HIGH-RESISTIVITY ANOMALY SELECTION

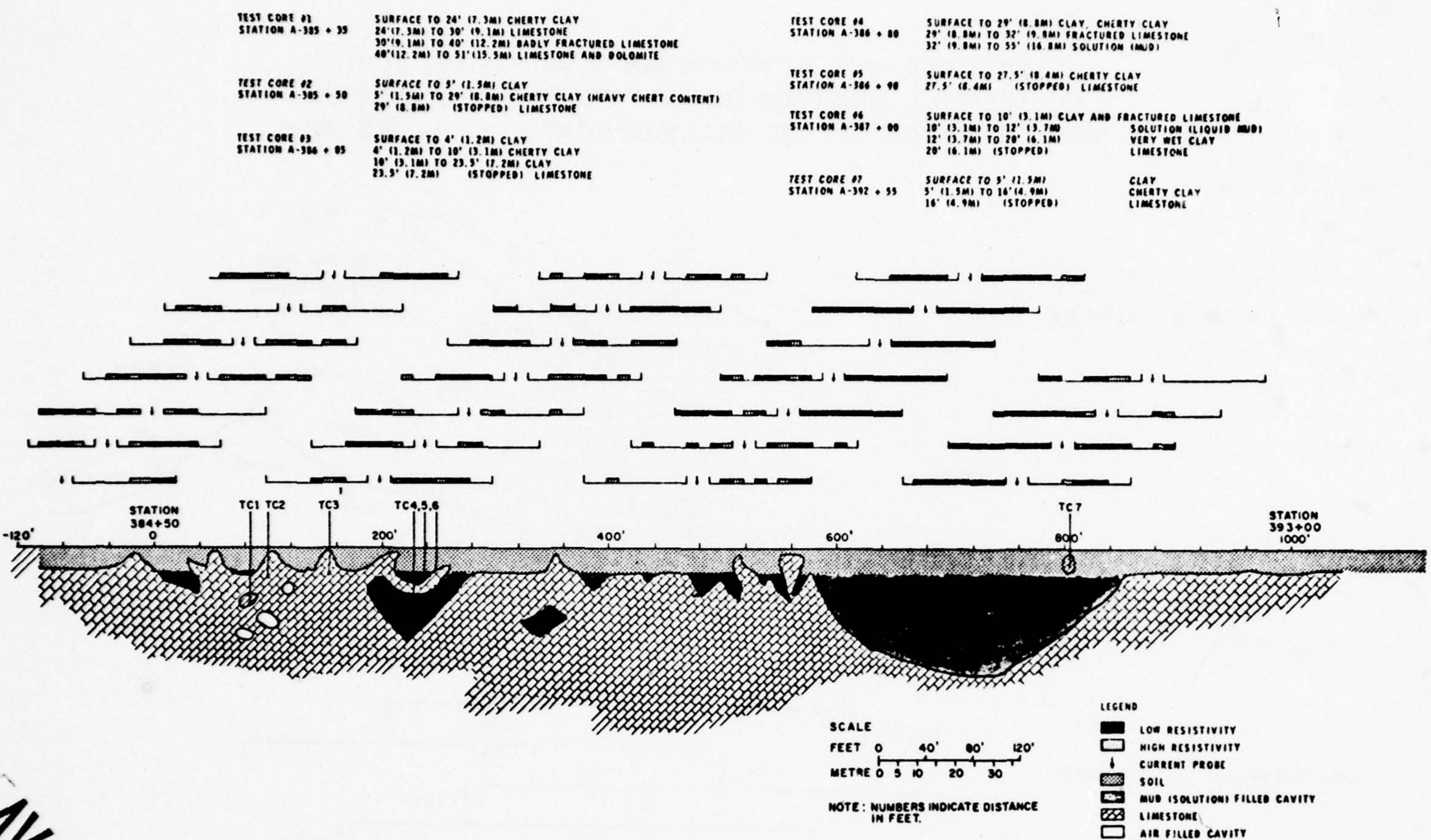


FIGURE 5
VERTICAL PROFILE UNDER SURVEY TRAVERSE A,
INTERSTATE HIGHWAY 59 TEST SITE, BIRMINGHAM, ALABAMA

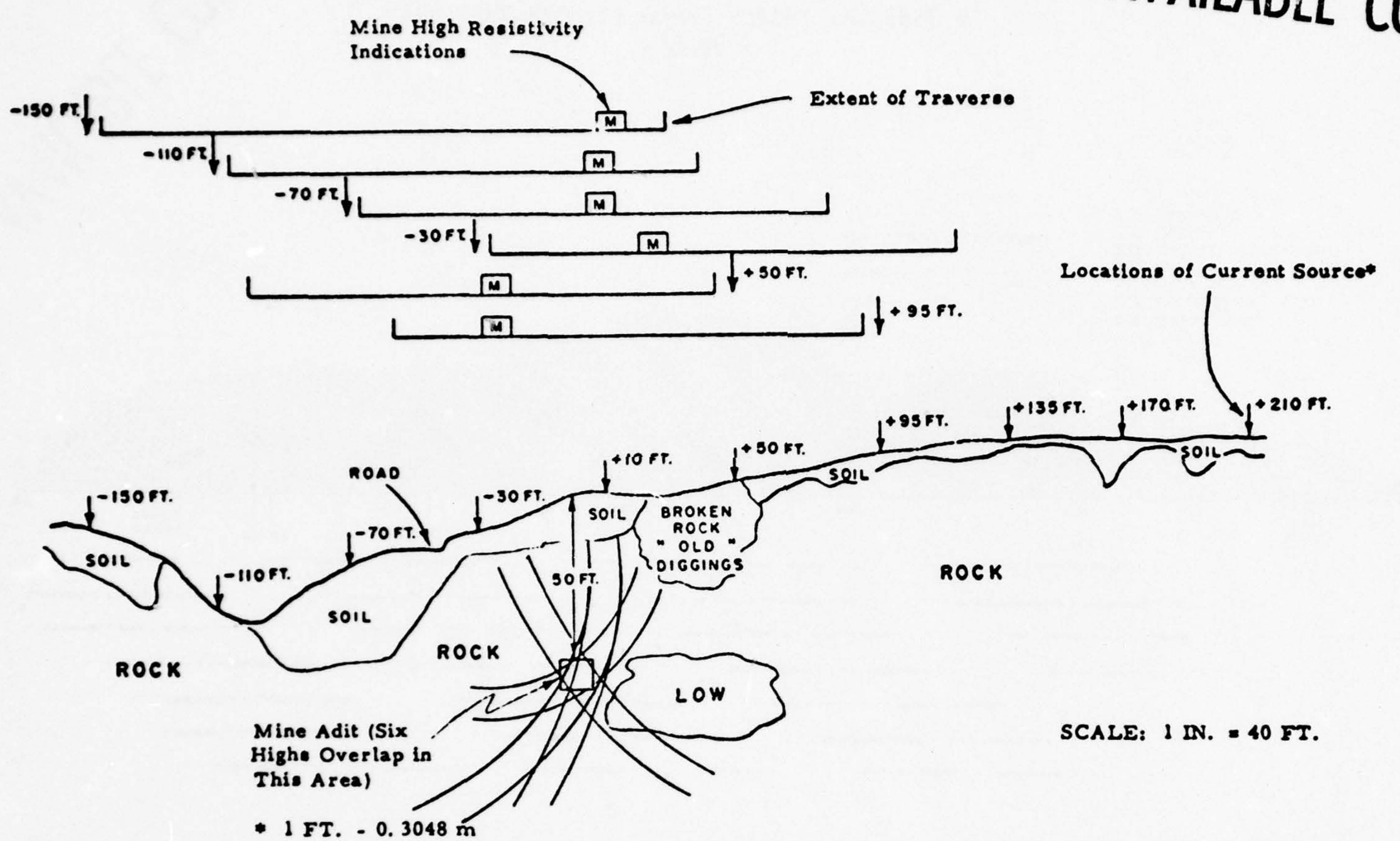
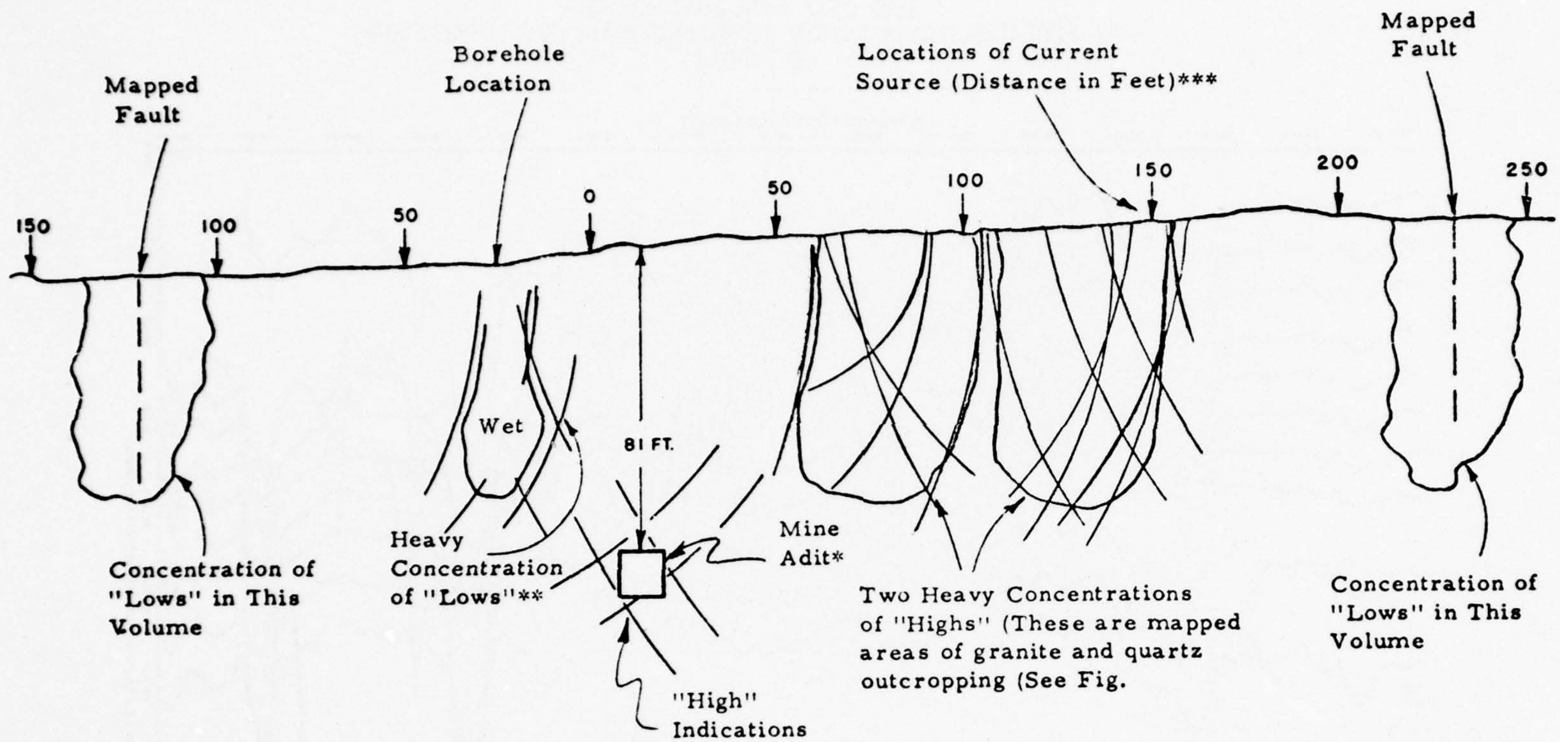


FIGURE 6. INTERPRETATION OF RESISTIVITY DATA ALONG TRAVERSE A, IDAHO SPRINGS, COLORADO
(Only resistivity high's caused by mine are shown)



NOTE: Only parts of arcs are shown that contribute to or outline major features.

* 6 arc pairs crossed at adit location
** 8 arc pairs crossed in the wet location of the borehole
*** 1 FT. = 0.3048 m

FIGURE 7
SKETCH OF EARTH RESISTIVITY INTERPRETATION OF A TRAVERSE ALONG SURVEY LINE 7, GOLD HILL, COLORADO

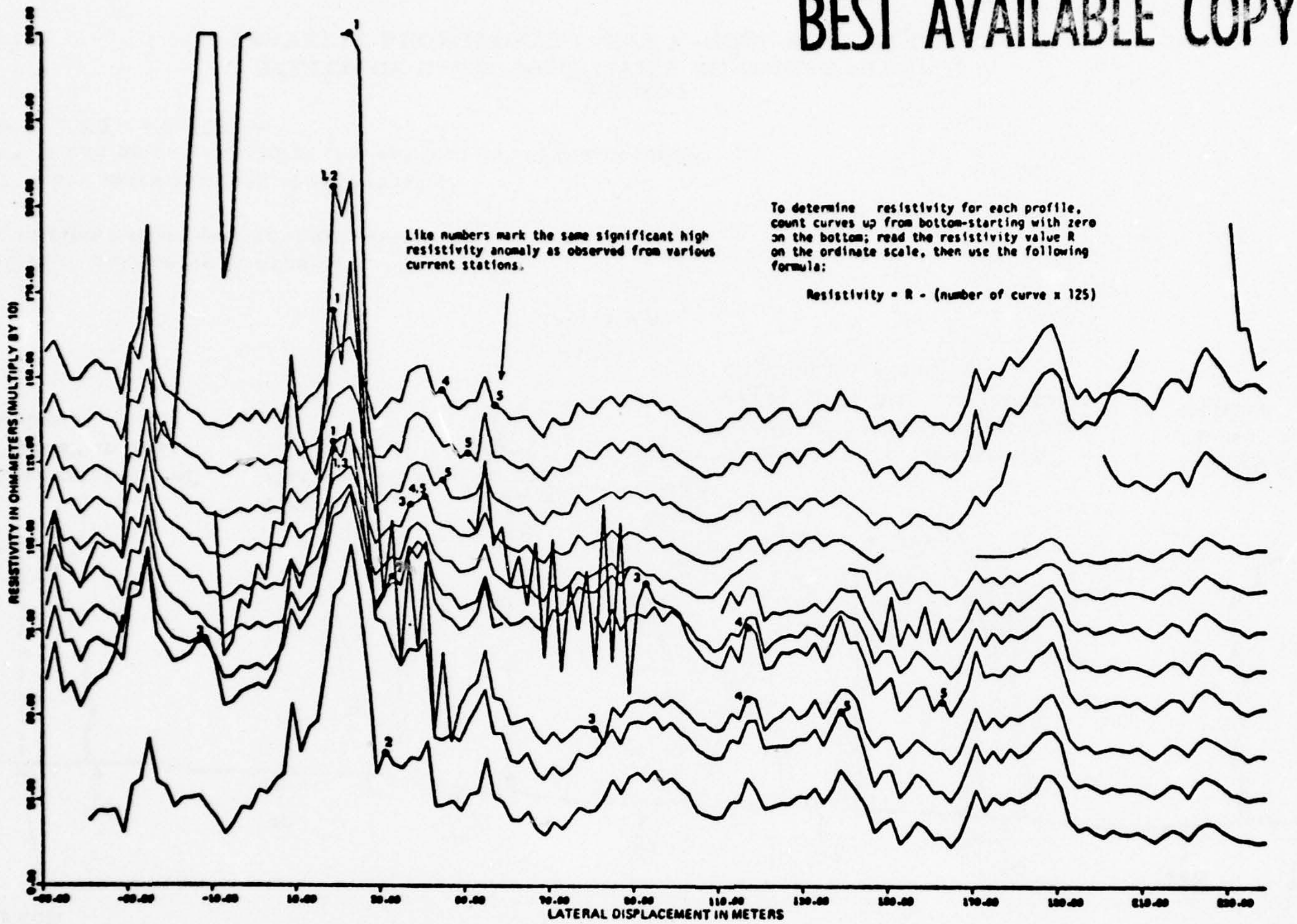


FIGURE 8
COMPUTER-PLOTTED PRESENTATION OF RESISTIVITY FIELD DATA FOR COPPER/ZINC MINE TEST SITE

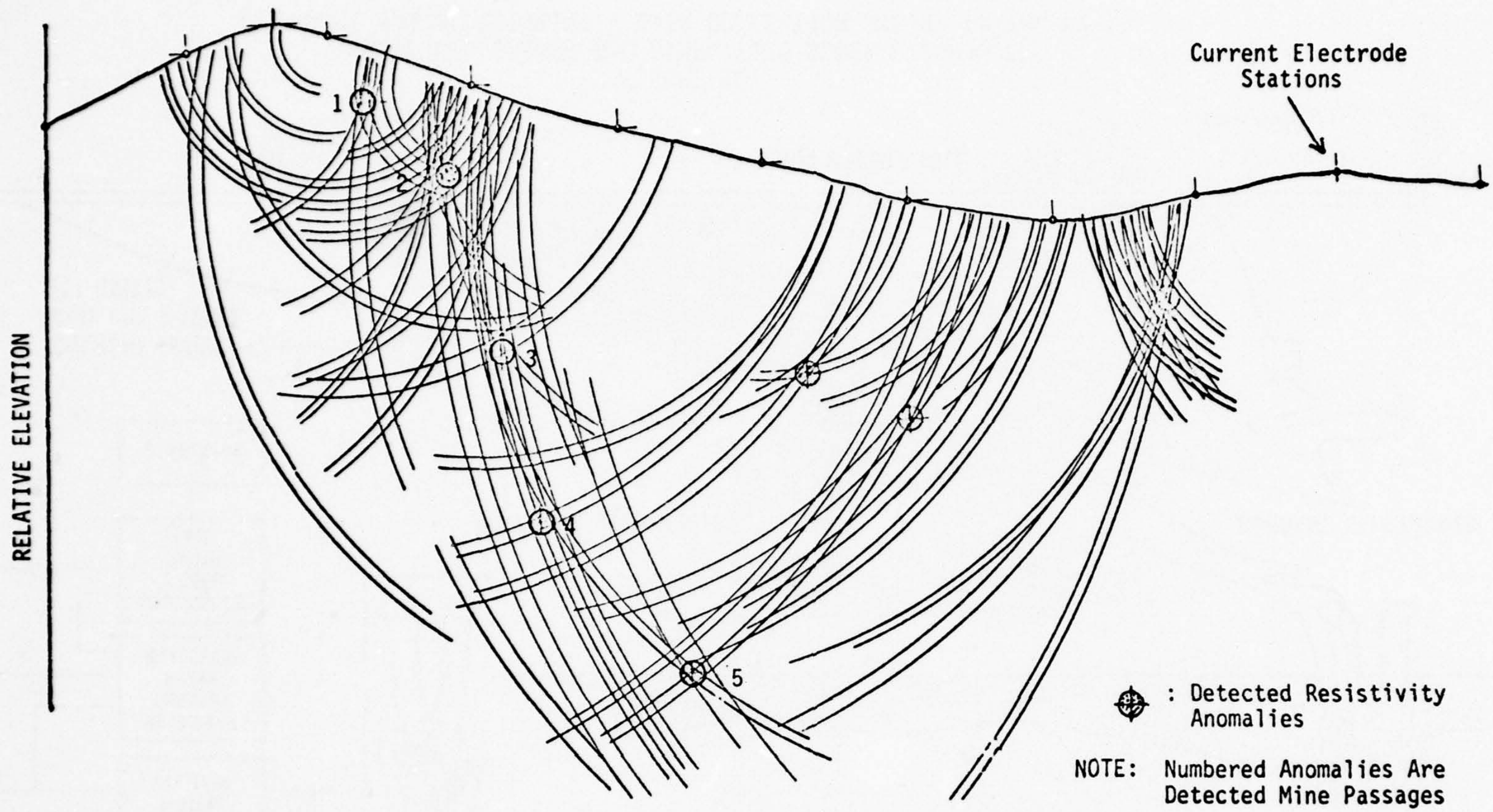


FIGURE 9
DETECTED RESISTIVITY ANOMALIES AT A
COPPER/ZINC MINE TEST SITE

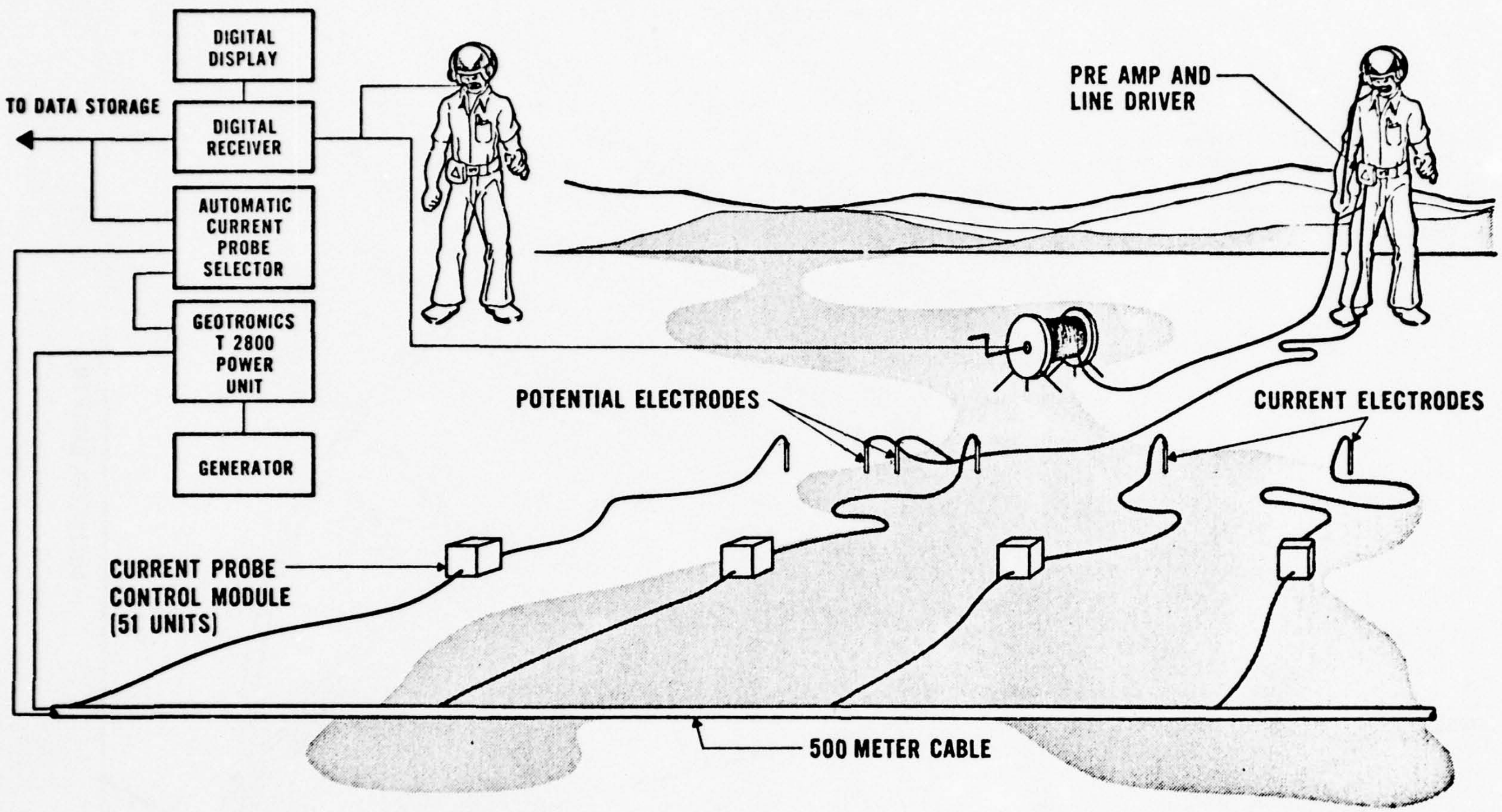


FIGURE 10
CONCEPTUAL SKETCH AND SIMPLIFIED BLOCK DIAGRAM OF
AUTOMATIC EARTH RESISTIVITY DATA COLLECTION SYSTEM IN THE FIELD

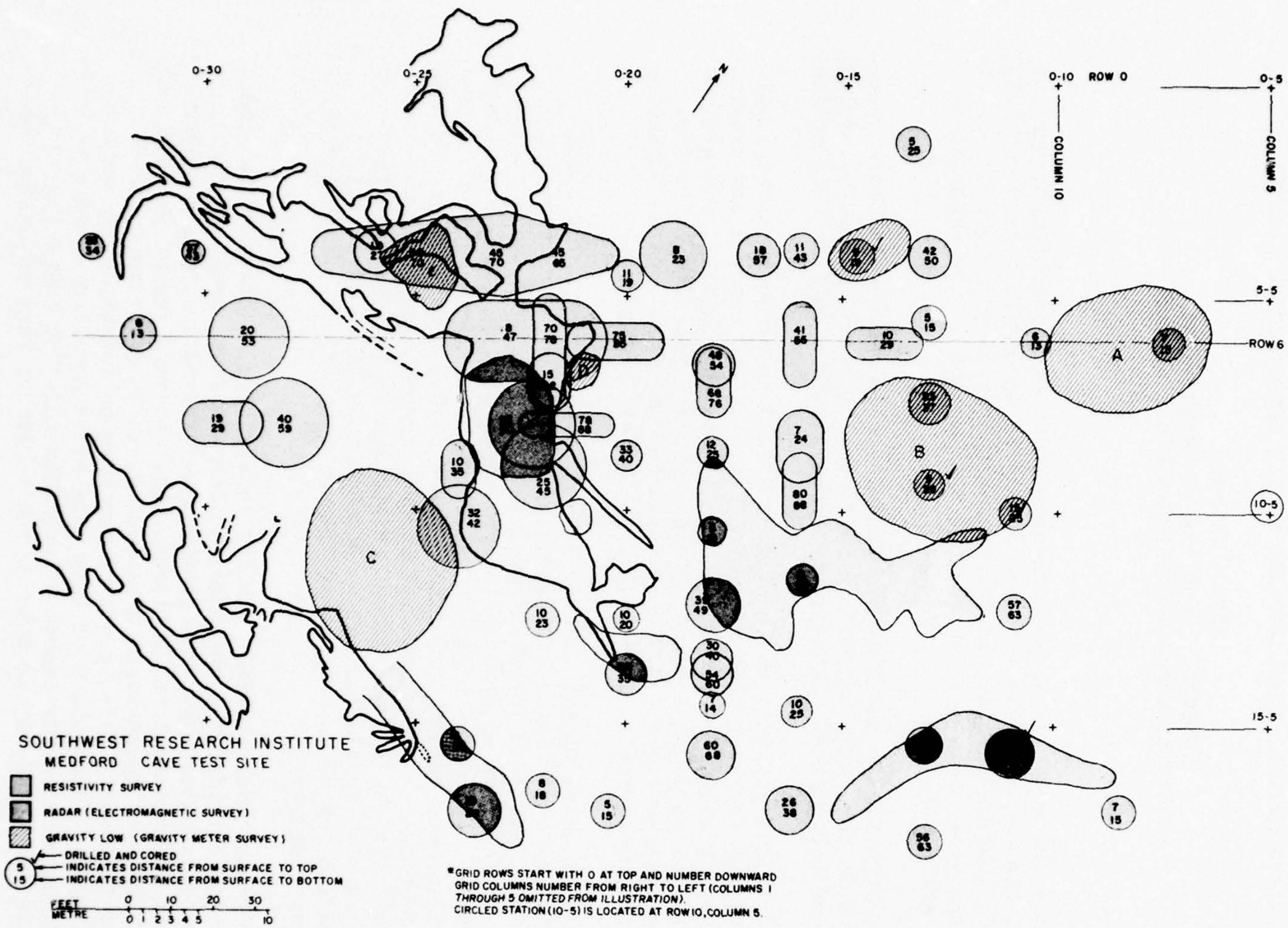


FIGURE 11. LAYOUT OF THE MEDFORD CAVE SITE SHOWING OUTLINE OF CAVE AND LOCATIONS OF UNDERGROUND ANOMALIES AS INDICATED BY THE THREE REMOTE SENSING TECHNIQUES

MICROGRAVITY METHOD APPLIED TO THE DETECTION OF CAVITIES

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Abstract

Among the geophysical methods devoted to the detection of shallow cavities, Microgravity was the last one to be developed to an industrial stage. In western Europe, the increasing number of gravity stations observed each year since 1963 shows that this method is now regarded as the most efficient.

For significant results, Microgravity requires an elaborate technique both in the field and during interpretation. Refinements, useless for most of the conventional gravity surveys, are a must in this method.

A critical point is the quality of field observations; they must be carried out and evaluated very carefully. Since 1969, a new gravity-meter, the "Microgal," manufactured by LaCoste and Romberg, was evolved from their standard Model G and offers increased potentialities for shallow gravity surveys. Both the measuring accuracy and the surveying speed were substantially improved by using this new meter.

Another critical point lies in the method itself. The final result of a microgravity survey is a map showing the variations of density in the shallow levels. Density depends on many factors, and it is no wonder that an anomaly interpretated as a man-made cavity may finally be recognized as a geological structure. In many cases, it is easy to eliminate such interferences found in other techniques, such as ore-prospecting. A convenient solution is the complementary use of another geophysical method, either refraction seismic or electrical sounding in that particular case. Both methods yield quantitative results which may be used to remove the gravity effect of the identified geological feature.

There are many problems related to cavities, natural or man-made, from the largest (Karsts, quarries) to the smallest (small sinkholes, saps, and galleries), and many people are involved in those problems: geologists, archaeologists, builders, etc. As very few of these people are familiar with geophysical prospecting, it is of prime importance not to disappoint them. This is one of the reasons for which the author wrote in 1965: "The future of this type of exploration appears to us as depending more on the number of problems rejected for which microgravity is inadapted rather than on the number of surveys carred out."

Since then, we have found that microgravity takes advantage of favourable events frequently associated with underground cavities. This is what is called "the secundary effect" caused by different phenomena

(joints, dissolutions, collapses) all resulting in a common consequence: a decrease of the bulk density, therefore emphasizing the original gravity anomaly. In several instances, the secundary effect appeared to be three or four times greater than the anomaly relating to the cavity itself. This major feature was highly emphasized in 1973 during an International Congress of Engineering Geologists, held in Hanover (Germany), partly devoted to the problems connected to cavities. It was recognized that the "secundary effect" gives microgravity an obvious advantage over such methods as electric or seismic which do not give any significant information regarding that kind of structures.

Another well-known advantage of gravity surveys is the ability to be carried out in urban areas without major problems; this is not a characteristic of most other geophysical methods and is one of prime importance as the detection of cavities is very often related to the development of urban areas (new buildings, freeways, etc.).

These concepts are illustrated by a few examples. Among them we shall show the finest possibilities of the method using mathematical processing to increase the resolving power of the gravity results.

Microgravity Method Applied to the Detection of Cavities

By Robert Neumann

Ladies and Gentlemen,

Let me bring the old South the greetings of old Europe, together with the French way of thinking about the detection of underground cavities. I have been involved in microgravity from its inception. It is now a healthy teenager, but I must deplore the small amount of material relating to gravity in this symposium: only one paper devoted to this subject, and moreover from France. Are there really no microgravity case histories available in the U.S.? If a symposium like this one were organized in Europe, the number of gravity papers would account for 50 percent of the geophysical subjects. Such a difference between the two continents is surprising and deserves some attempt to understand the situation and to improve it.

Despite the fact that technical subjects are the prevailing ones, the economical point of view will be considered first. The total number of gravity stations measured by C.G.G.'s crews for cavity detection since 1968, must be close to 150,000, and this figure might be doubled if one takes into account the other geophysical companies. Taking a mean value of 20 dollars per station, the money involved in microgravity prospecting in Western Europe would amount to six million dollars. Of course, much more money is involved in geophysical prospecting for oil, but this amount is quite usual for geophysical ore research. Thirty thousand stations per year means about a hundred different surveys and fifty crew months. This is quite considerable and demonstrates that microgravity has reached an industrial stage, at least in Western Europe. Information from Eastern Europe shows that several countries use microgravimetry with interesting results, despite the fact that, to my knowledge, their instruments do not achieve the high degree of accuracy of the "Microgravimeters". I have also to mention a few surveys carried out around the Mediterranean Basin, in northern Africa and the Middle East. In these countries there are some particularly attractive problems, and among them Egyptology.

The microgal meter plays a major part in the successful life of microgravity. It is built in this country, not so far from here, by Lacoste and Romberg, Inc. who are well known in this field. The idea of such a meter occurred to me nine years ago, in the middle of 1968, as a development of the excellent standard "Model G". Having accepted my request, Dr. Lacoste succeeded in his task by the end of the year and sent to C.G.G. (France) the first microgal meter "Model D" which has been operating perfectly since the beginning of 1969. Since this date, some 20 meters of this type have been manufactured, which is a large number for experimental

purposes but very few for an industrial development. The gravity market might be at least as important as it was during the golden age of oil prospecting. Of course, such a development would require so many microgal meters that other constructors would have to be involved. At the moment this is only wishful thinking, but I am not too despondent when I remember that my first experiments in this field were performed in 1948, whereas the first microgravimetric survey was carried out in 1963. So it might not be too late to convince the numerous American Geophysicists and potential customers, which is the only way to achieve such a development. And if you think I am dreaming about the future of microgravity, remember that the change of scale from reconnaissance to fine detail means that, instead of one station per square kilometer, the number of stations grows to 10,000 per square kilometer.

I strongly emphasized the microgal meter, because this instrument plays a leading part in the present development of microgravity both for economic and for technical reasons. Using a standard meter, it was usual to take 3,000 different readings to conclude 1,000 stations: this was necessary to increase accuracy and prevent errors. Such a repetition coefficient hindered the production and, consequently, the development of the method. Today, the same 1,000 stations require 1,200 to 1,300 measurements only and actual production has more than doubled. At the same time, accuracy has been increased substantially. Where in normal conditions a standard meter gave at best two hundredths of a milligal (20 microgals), the Model D offers an accuracy close to four microgals.

This gain in precision is illustrated in Figure 1 by the comparison of results obtained from a profile which was surveyed twice (it was along a freeway in Belgium). We were fortunate enough to extend a normal gravity carried out with a microgal meter to a part of a previous survey performed with a standard meter, perhaps not a good one and without the sophisticated quality checks mentioned above. The results are very instructive for at least two reasons:

1. The profile corresponding to the standard meter shows two negative anomalies, each of them enhanced by more than 0.04 milligal, which is highly significant in this area, as will be seen later. These anomalies were drilled without result, and this is no wonder if one refers to the other profile.

2. This profile is particularly smooth, and this has to be attributed, on the one hand, to the quality of the instrument and, on the other, to the absence of "lithological noise",i.e., the absence of density contrast within the superficial formations.

It is well known that handling a modern gravimeter is easy. This is true only when the requirements in terms of accuracy are not too critical, as in oil prospecting, which is by far the largest consumer of gravity measurements. In this field, the task of an operator is to secure an accuracy of 0.05 milligal with a meter, able since 1940 to give 0.02.

Such a comfortable situation certainly offered some advantages in standard surveys. Unfortunately, this is one of the reasons why the advantage of microgravity is not recognized everywhere. To my knowledge, a lot of tests were performed in many countries where no experienced operators were available, so that the results might very well look like those shown on Figure 2. This is an eloquent comparison between map A, obtained by an operator who was not able to do more than "take readings" and map B obtained under the same conditions by an experienced microgravity operator. I think further comment is needless, but I very much like Figures 1 and 2 because they point out the reasons why microgravimetry has sometimes failed to provide the expected results, and why the opinion of many "specialists", who have never operated a gravimeter, is set firm against the potentialities of microgravimetry.

There is another topic that deserves exhaustive discussion and a number of figures, but it is too large a subject to be developed to any extent here. I mean the choice of a convenient grid of stations tailored to the geophysical problem. This important choice obviously depends on the geometrical properties of the "structures" to be detected, including their depth. The fishing net selected has to have a mesh adapted to the size of fish to be caught. The problem is not so simple because economic considerations always interfere with technical ones. Recently, an interesting device derived from the "telelog" used in oil research, has given some support in this matter. Thanks to an electromagnetic apparatus, it is now possible to detect an underground cavity in the vicinity of a drillhole within a distance of about twelve meters. When a drillhole, located on a gravity low, poorly defined by a too wide grid of stations, has failed to meet the corresponding cavity, this new telelog offers another chance to locate the spot, giving some flexibility in the choice of the grid.

Among the largest features which may be found by microgravimetry are karstic cavities caused by dissolution phenomena in limestone, and their detection is easy provided when they are not too deep. Such favorable circumstances are met in many fields: archaeology, mining, speleology and, of course, civil-engineering. Nevertheless, it is amazing to observe that karstic problems are so seldom brought to the attention of the gravimetricians.

The following example (Figure 3) is taken from a survey carried out in Italy. The drilled hole located at the center of the anomaly intersected a cave between 4 and 16 meters. Despite the size and shallow location of this cave, it is remarkable that a map of the apparent resistivity obtained from direct current measurements does not give any significant indication fitting the gravity anomaly.

In the case of Figure 4, the role of electrical results was somewhat better, when it appeared that a drillhole located at the center of this new anomaly did not intersect any void between the surface and a depth of 25 meters. Other geophysical results, resistivity and seismic refraction, showed that the rock was replaced locally by loose material with, of course, a low density. It was later shown that several karstic cavities had been filled with detritic material carried by a creek from a nearby hill.

Even more than karstic problems, the detection of old underground quarries is the privileged domain of microgravity. One of its main fields of application is the northern part of France where the documents related to quarries (maps, surveying) have been lost or destroyed during the First or Second World War. Part of a survey carried out in the North Department is shown at Figure 5. The negative anomaly, A, corresponds to a known quarry, so closely that the residual gravity contours follow its limits exactly. Therefore, it was logical to consider that anomaly, B, which is of the same magnitude, i.e., more than 0.15 milligal - a large value for this type of survey - had a similar origin. An additional observation supporting this interpretation was the fact that anomaly B extends along the eastern fringe of another known quarry outside the surveyed area. Moreover, several sections across B and A showed that both anomalies were members of the same family. Despite these facts, 15 drillholes located on B did not intersect any cavity. This is an example of a fortunately rare occurrence where a well defined gravity anomaly with a geological cause was interpreted as related to a quarry. It must be added that, because of the numerous successes of microgravimetry in the region, this unique failure did not reduce the confidence of the users. But it indicated the limits of the method and marked a step towards a convenient procedure for identifying, and then removing, the geological anomalies from our gravity maps.

The solution consists in using another geophysical method in conjunction with microgravimetry, in order to give a picture of the geological conditions, including the variations in thickness of different layers as well as their lithological changes. In the first case, it is important to get quantitive information because this makes it possible to compute the gravity effect of geological layers and then remove it from the Bouguer map. This is a well known operation called "stripping", developed by the American Geophysicist, Sigmund Hammer. The need for quantitive results restricts our choice to two methods only, refraction seismic and electrical soundings. The first one seems the better though it is sometimes limited by an improper sequence in the velocities, as when an interesting layer is slower than the terrain above. Electrical soundings do not suffer from such a drawback, but quantitive interpretation is more delicate. The choice between these two methods has to be adapted to each specific case. Of course, neither seismic nor resistivity are available if the geophysical problem is located downtown or nearby.

Another example of quarry detection in the North of France, shown at Figure 6, does more than compensate for the failure described above. Here the anomaly barely exceeds 0.05 milligal, because of the relatively great depth of the quarries in this area, about 16 meters. Furthermore, the shape of the quarries is like a Swiss cheese, where the volume of the voids is smaller than the volume of material. Under such conditions, it is evident that the geophysical results give more information than a few isolated drillholes. There is no doubt that if the drillers had not persevered because they had no confidence in microgravimetry, these quarries would not have been found. Another important lesson can be drawn from this example. When the quarries, after their discovery through drillholes,

were explored and almost perfectly delineated, it became possible to calculate their gravimetrical influence, which was estimated to be less than 0.02 milligal, i.e., one third of the observed anomaly. This is a marked example of what is called the "secondary effect", a well known phenomenon, very often associated with underground cavities. This effect is due to different events (cleft, dissolution, collapse, etc.), occurring in the layers above the cavities, and all working in the same direction, towards a decrease of the bulk density, and helpfully located right above the voids. So the gravity minimum due to the cavity itself is significantly enhanced by the effect of those secondary density contrasts, without any distortion. It is remarkable how closely the gravity contours follow the limits of the danger area as it is presently known. It appears that the gravity method takes full advantage of favorable circumstances, which certainly do not play the same role for other geophysical aids, like the electric or seismic methods. This important point was strongly emphasized in 1973 during an International Symposium of Engineering Geologists held in Hanover (Germany), partly devoted to the problem of cavities.

Results of the same quality as the above example have prompted geophysicists to apply microgravimetry to more delicate problems related to small shallow cavities. Figure 7 is taken from a survey carried out on a freeway and the result is among the finest which can be shown. The anomaly barely exceeds 0.03 milligal and it is interesting to observe how the contours are affected by an old underground gallery partly filled in. In this case it was not necessary to drill the anomaly because a collapse occurred after completion of the survey when a light post was being set up. This does not imply that anomalies of this magnitude are always due to cavities. They may be attributable to the "lithological noise", originating in the weathered zone. However, it may happen that, as in the case of Figure 7, the noise level is so low that anomalies can be considered significant. This is demonstrated by the profile of Figure 1 called "Microgal gravimeter" which is situated in the same region and clearly shows the low level of lithological noise.

Nowadays, it is well understood that a Bouguer map remains tied to the elevations of the field stations, the different corrections: free air, Bouguer plate and terrain correction do not reduce the Bouguer values to what they would have been if all the observations had been made at the altitude of the datum plane and on a flat ground.

The gravity effect of a given body depends on the relative position of the point of observation with respect to that body. The corrections made do not affect that geometry, and particularly not the distances, so that on a Bouguer profile, the anomalous effect of a given body is still dependent on the individual elevations of the stations.

For very shallow problems, which are frequent in microgravity, variations of about one meter in the elevations may distort the shape of the anomalies and interfere with interpretation.

Let us consider a spherical body with its center of mass three meters deep, resulting in an anomaly of three hundredths of a milligal. For the same body placed at a depth of four meters, the resulting anomaly is broader but its amplitude is reduced to 1.7 hundredths of a milligal, the reduction amounting to 13 microgals. The shape of the Bouguer anomaly resulting from that particular body closely depends on the relative elevations of the field stations along the profile and shows a marked distortion with respect to the theoretical profile calculated on a horizontal plane. In particular, the minimum of the anomaly is shifted towards the lows of the elevation profile and is no longer located at the vertical of the center of the body. The strictly precise solution consists of an upward continuation of the gravity field up to a given horizontal plane, generally taken at the level of the highest station. This process was applied to the following map (Figure 8) taken from a survey carried out in the suburbs of Paris. The map shows two houses in an area where sinkholes had been observed. The house located on the southern side is built on a slope, the ground level being one meter higher at the rear than at the front, and the basement the same height as ground level at the front of the house. Figure 9 shows the map reduced to a constant level: the negative anomaly is shifted by a distance which places the minimum outside the house, consequently, the risk associated with the anomaly is reduced. Unfortunately, on the northern side the anomaly detected under the other house, where there is no slope has not been displaced by the processing.

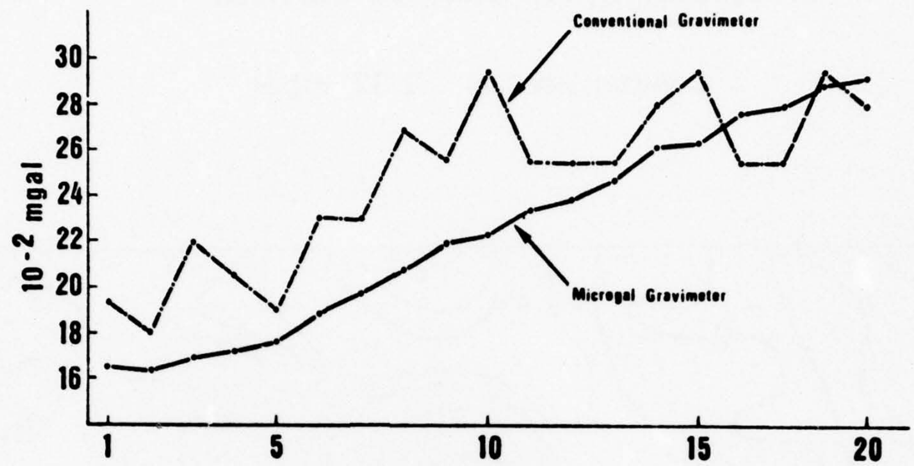
The above examples have shown how well the gravity contours may delineate the external limits of an underground quarry. A much more delicate problem is the separation of pillars from chambers when they are in an irregular pattern. Such a problem is related to the poor resolving power of the gravity field, due to its congenital myopia. The general solution consists in giving gravity such spectacles as processings or transformations of the gravity field, all working as filterings, even if continuations or vertical derivatives are concerned. The common characteristics of such filterings are that they enrich the high frequency components of a gravity anomaly and at the same time lessen the low frequencies. The width of the anomalies is reduced; increasing the resolving power.

In the case of Figure 7, the depth of the quarry was too large to allow any attempt to improve the resolution. Furthermore, as the main part of the anomaly was due to the secondary effect and not to the quarry itself, any processing would have been useless. On the other hand, this attempt was successful in the case of Figure 10. Here the quarry is formed by some "catiches" which have roughly the shape of bottles or funnels turned upside down. The bottle neck is an access shaft connected to a chamber separated from the nearby chambers by pillars of various shapes and dimensions. This type of quarry is fairly common in the North of France, especially where the limestones are very shallow, five meters or less, as is the case here. A first survey, carried out with a grid of 20 meters, had detected a negative anomaly of more than 0.10 milligals, leading to the discovery of a quarry including 11 catiches, which were found when the quarry was explored in detail, underground. Someone had the idea of

trying to identify each chamber individually using microgravity. A much more detailed survey was carried out with a dense grid of five meters (on Figure 10, the stations of the first survey are represented by larger dots). At first glance, the survey failed to give the expected information, as the anomaly was not separated according to chambers. Nevertheless, a careful examination showed some minor features with possible significance. A suitable processing, similar to the substraction of a regional anomaly, brought out local features, as shown by Figure 11. The gravity contours are now in reasonable agreement with the map of the chambers and correlation would have been even better if the accuracy had been improved by repeating the readings. This work should be considered merely as a successful test which makes clear that the possbilities of microgravity are not yet fully utilized.

The arguments and examples set out in this paper demonstrate that microgravity has left the experimental stage long ago and is now a valuable tool; though not yet as widely called for as it deserves to be. Like the other geophysical methods, microgravity has its limitations in close relation to geological and lithological interferences. Even when these interferences seem to overrun the expected information, it is sometimes possible to enhance the gravity results with the help of another method. The possibility of getting very high quality results through the use of microgal meters has greatly increased the efficiency of microgravimetry which is now one of the best geophysical methods applied to shallow problems, and among them to the detection of underground cavities.

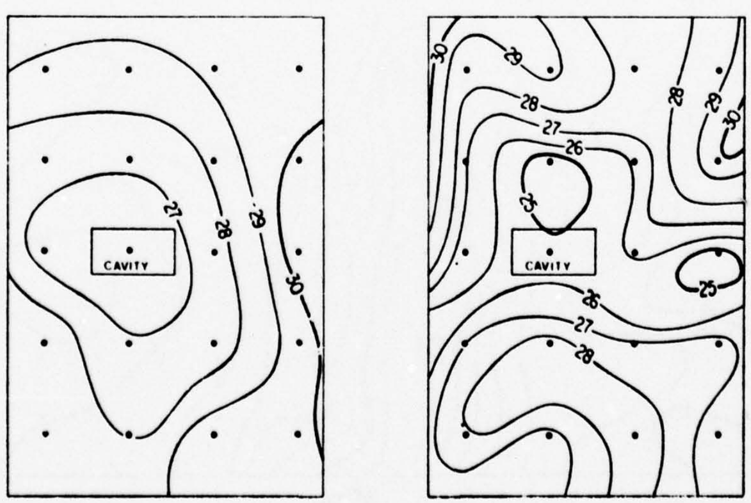
CONVENTIONAL AND MICROGAL GRAVIMETERS



HORIZONTAL SCALE : 10 m.

Figure 1

COMPARISON OF RESULTS OBTAINED
BY TWO DIFFERENT OPERATORS GRID 2 x 2 m



SCALE
2 m

Figure 2

DETECTION OF KARSTIC CAVITIES

Contour interval 0.02 mgal

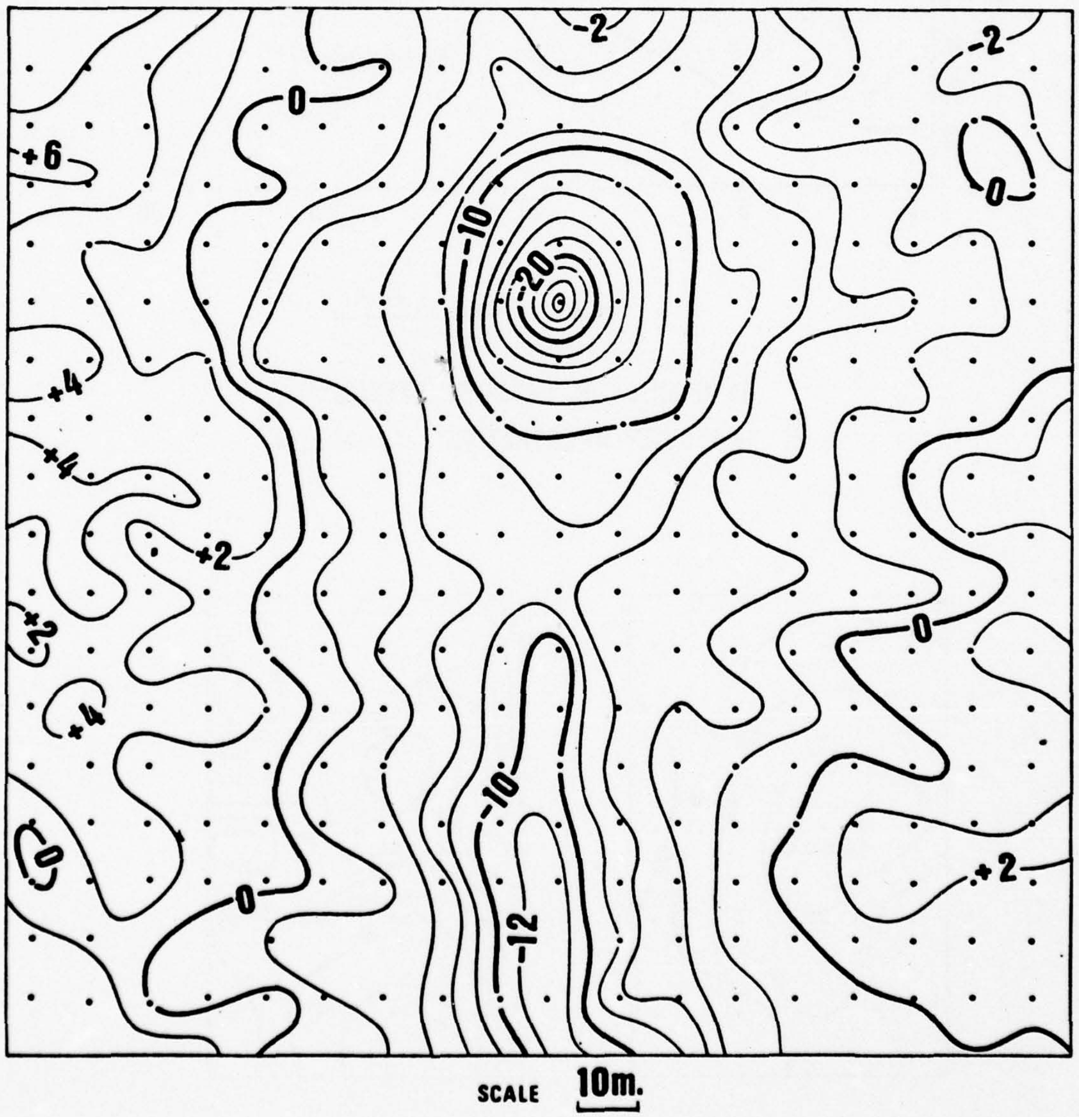
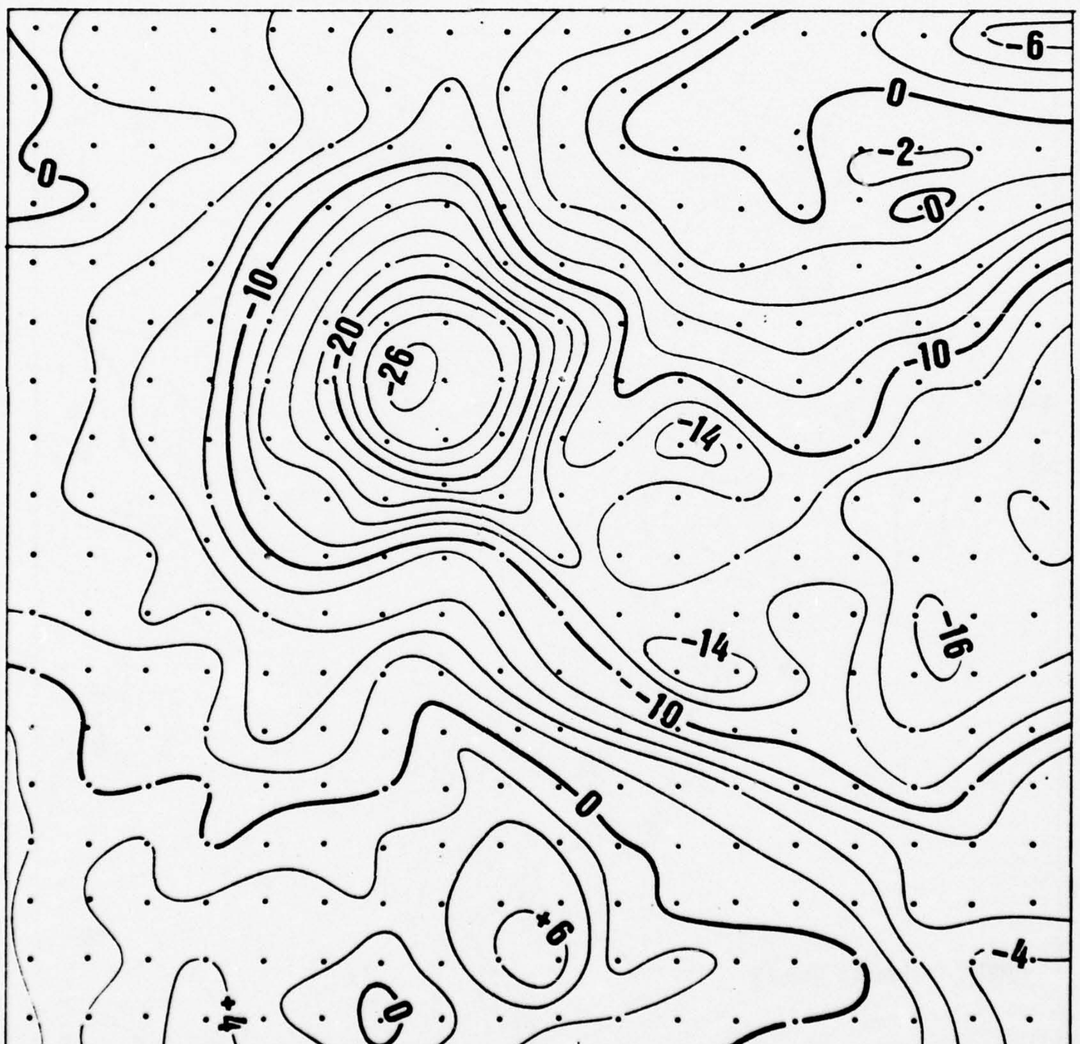


Figure 3

DETECTION OF KARSTIC CAVITIES

Contour interval 0.02 mgal



SCALE 10m.

Figure 4

DETECTION OF QUARRIES

Contour interval 0.02 mgal

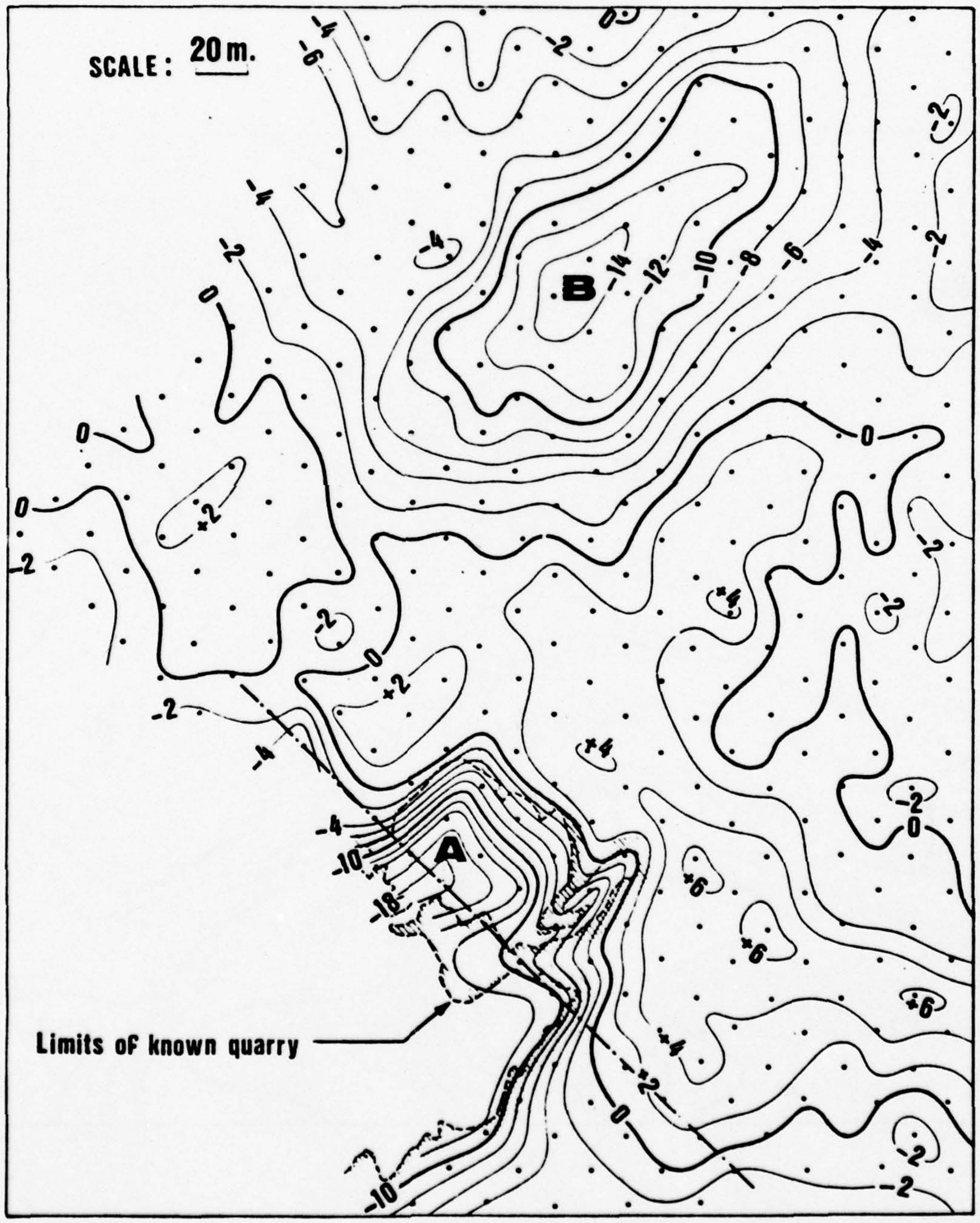


Figure 5

GRAVIMETRY AND DRILLHOLES

RESIDUAL ANOMALY

Contour interval 0.01 mgal

SCALE : 50 m.

Drillholes
- ◇ Solid rock
- ◆ Cavity

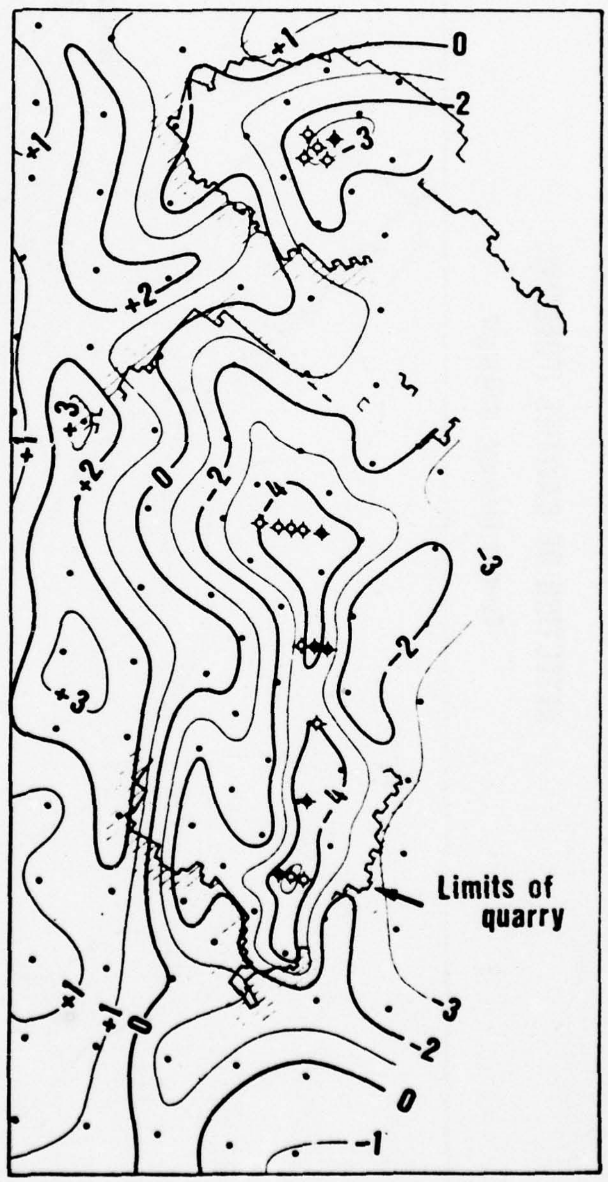


Figure 6

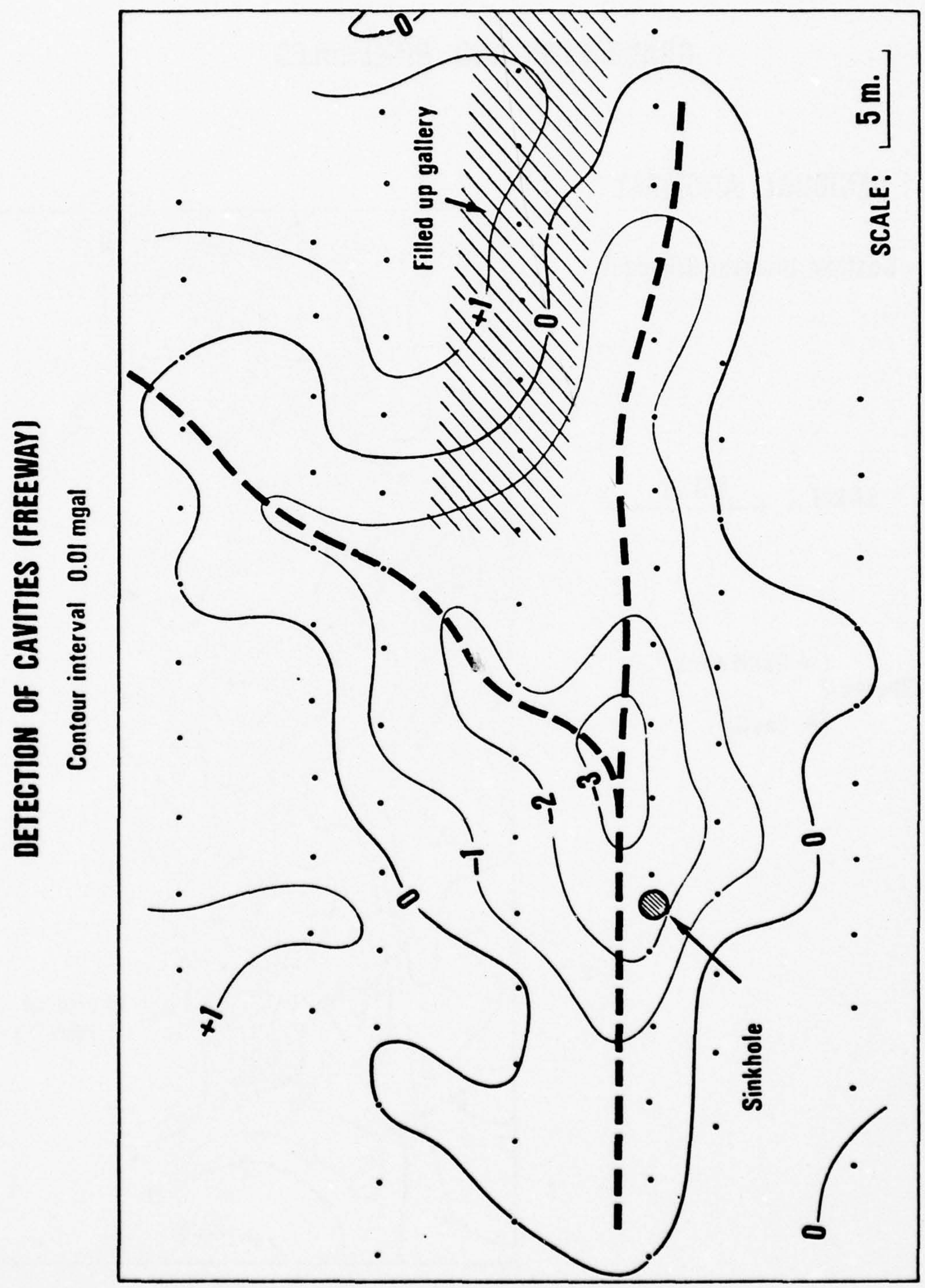

DETECTION OF CAVITIES (FREEWAY)
Contour interval 0.01 mgal
Filled up gallery
Sinkhole
SCALE: 5 m.
+1
0
-1
-2
-3

Figure 7

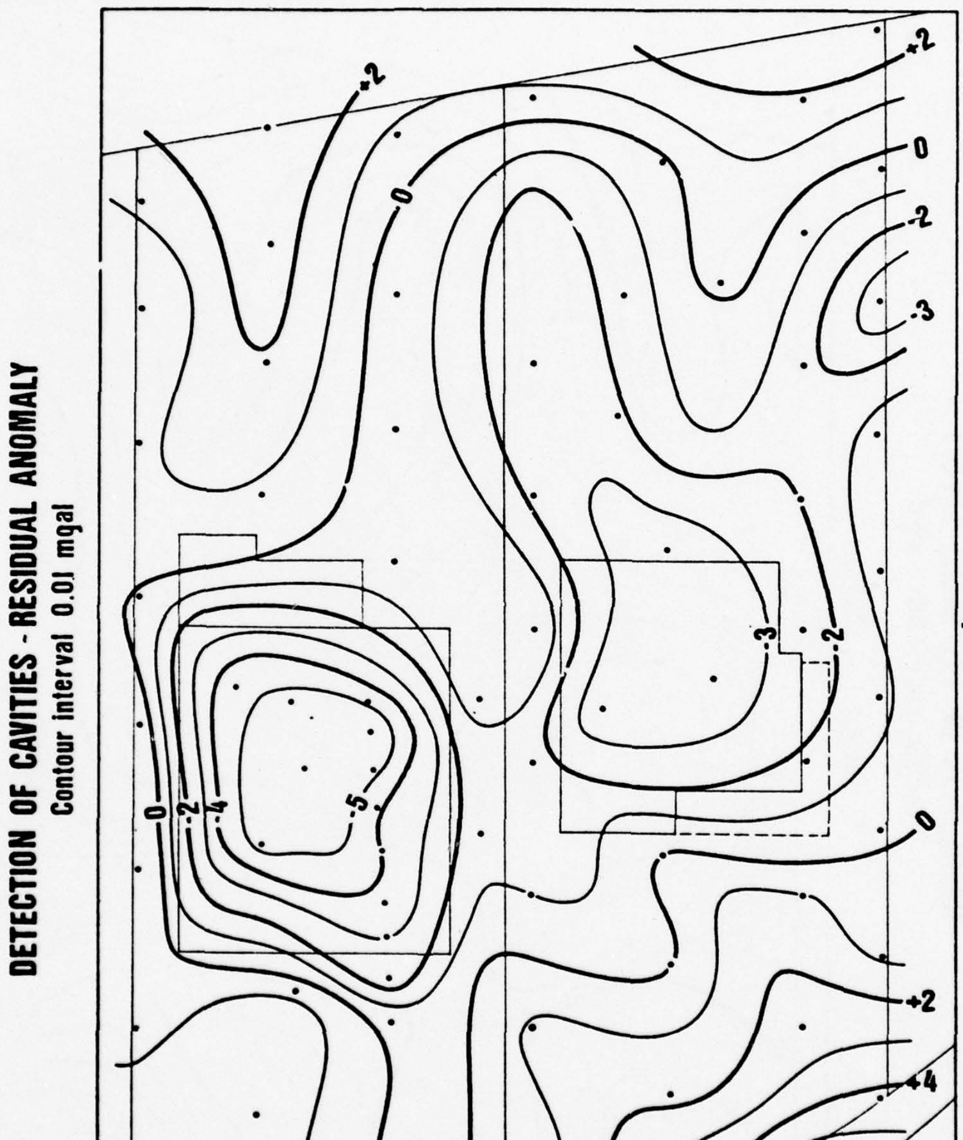

DETECTION OF CAVITIES - RESIDUAL ANOMALY
Contour interval 0.01 mgal
SCALE: 4 m.
+2
0
-2
-3
-4
-5
+1
+4

Figure 8

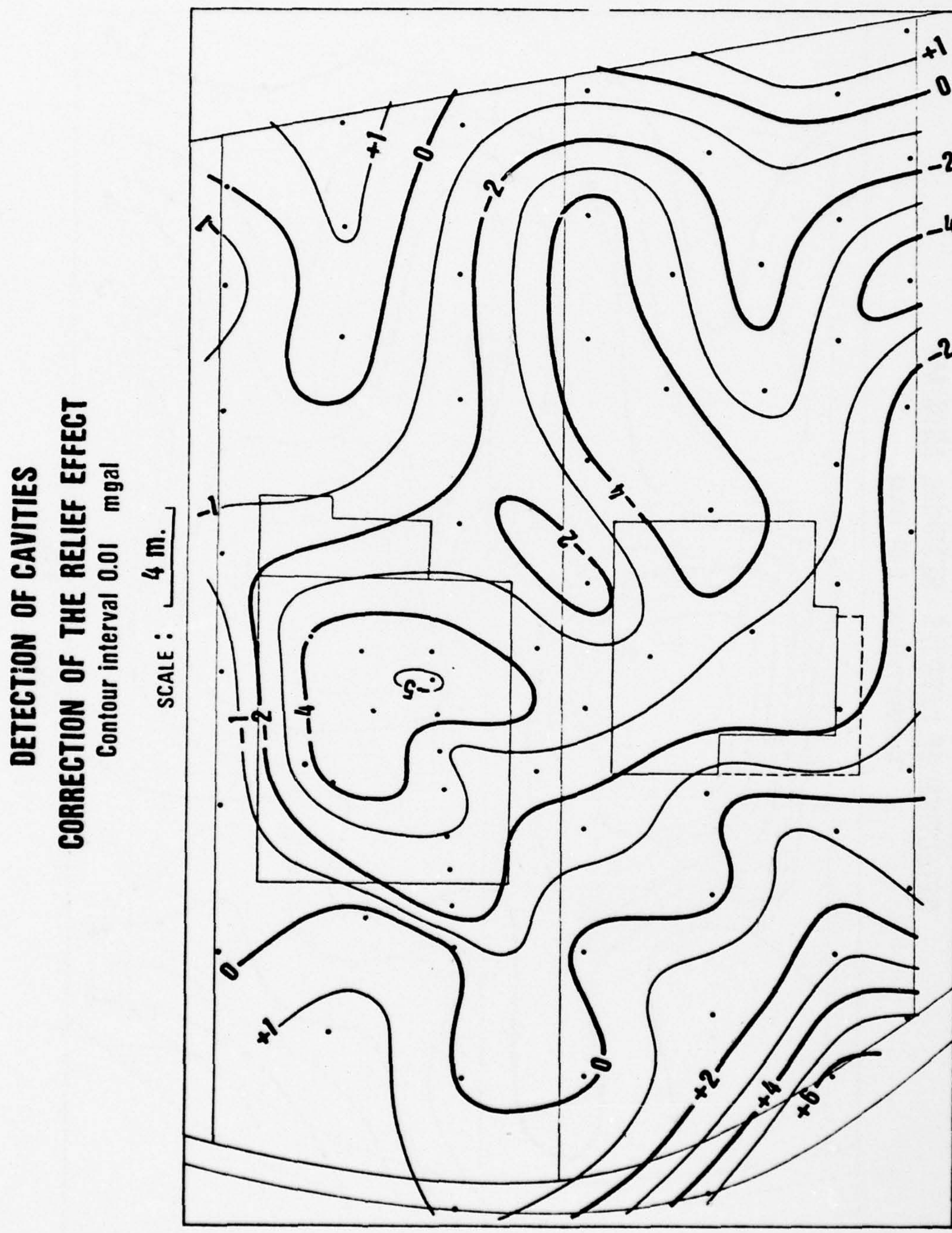

DETECTION OF CAVITIES
CORRECTION OF THE RELIEF EFFECT
Contour interval 0.01 mgal
SCALE : 4 m.

Figure 9

COMPLETE DEFINITION OF A QUARRY
BOUGUER ANOMALY

Contour interval 0.01 mgal

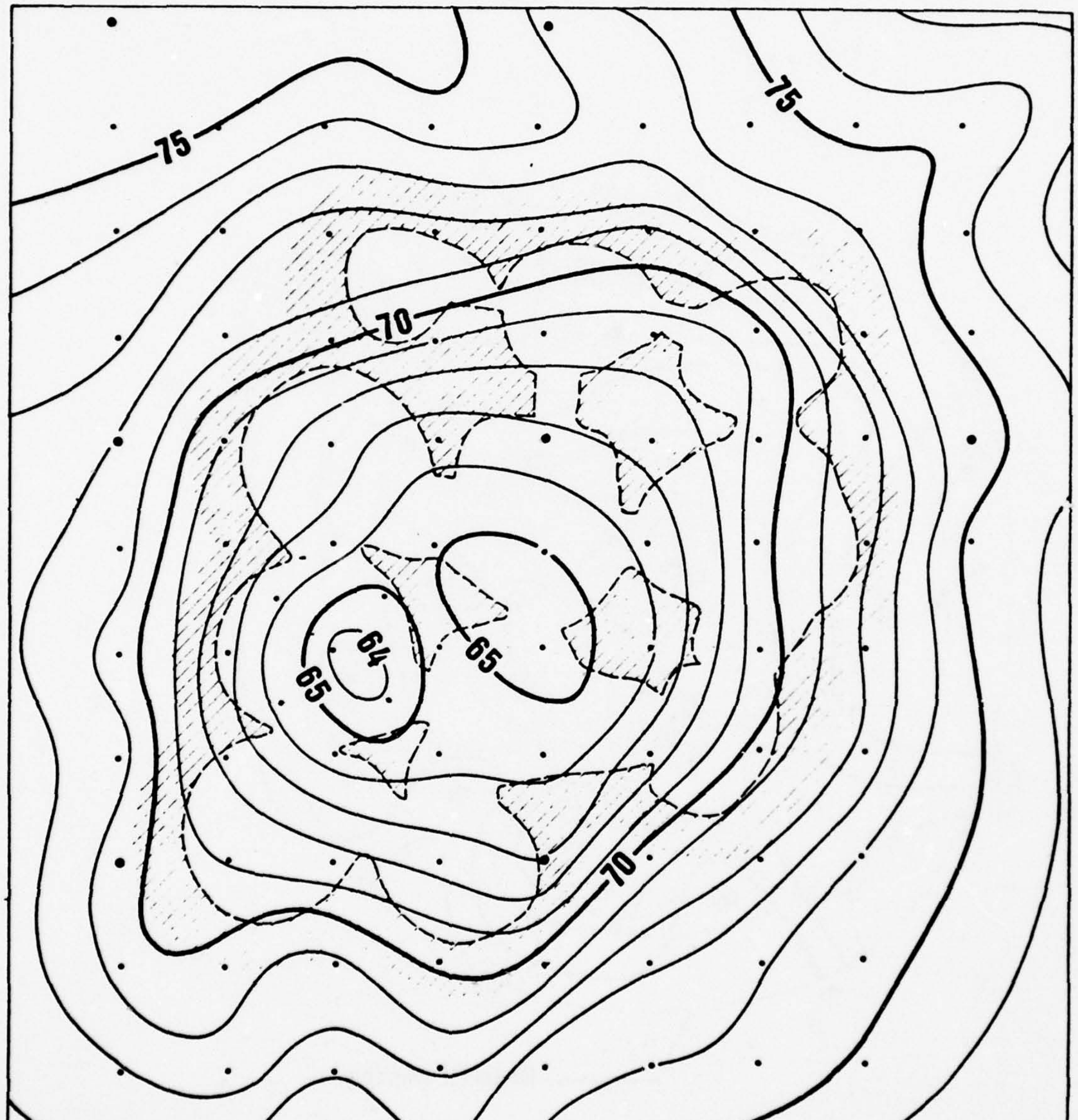


Figure 10

COMPLETE DEFINITION OF A QUARRY
REGIONAL AND RESIDUAL ANOMALIES

Contour interval 0.005 mgal

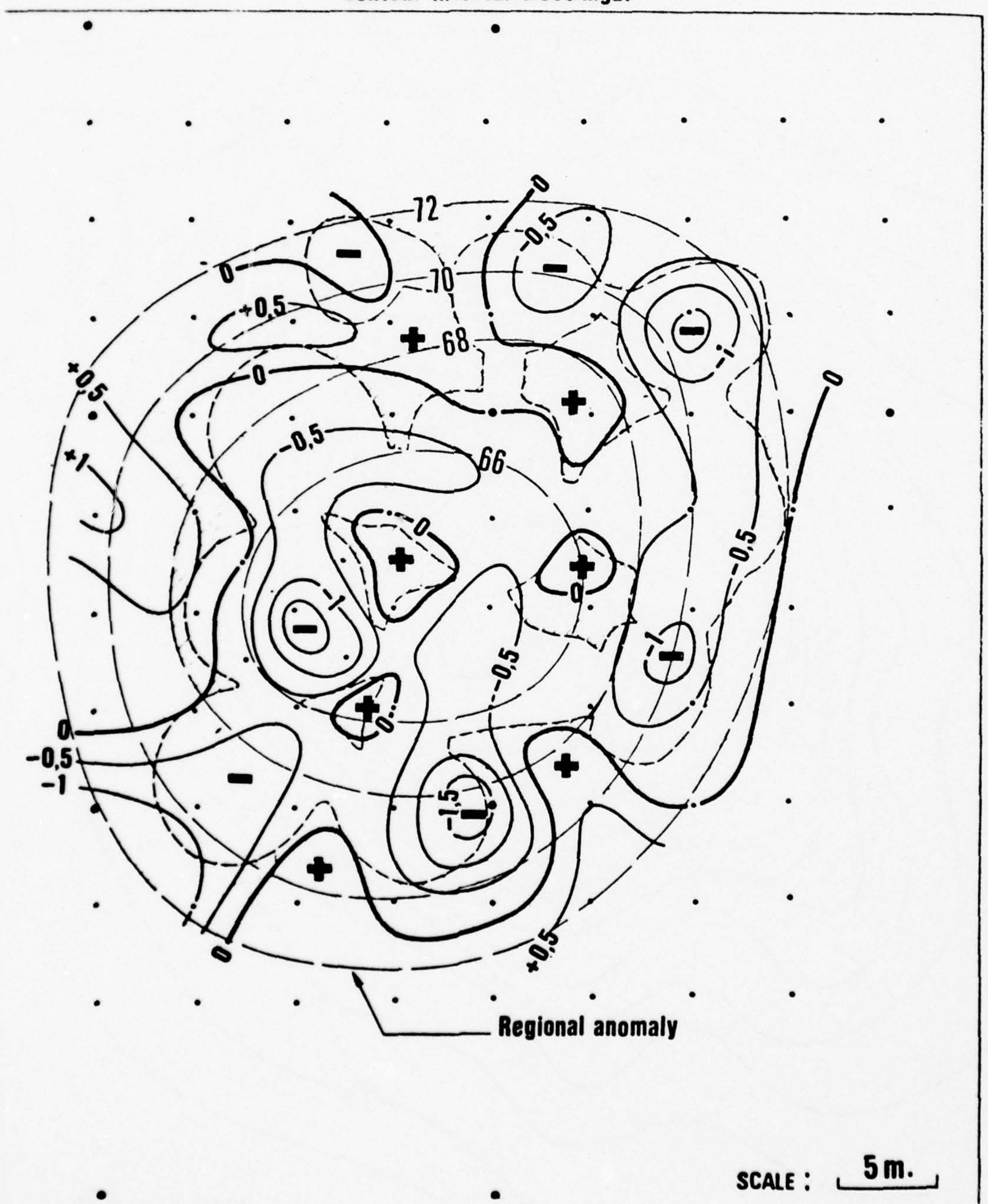


Figure 11

REVIEW OF DETECTION METHODS PRESENTATION

James B. Warriner
U. S. Army Engineer Waterways Experiment Station
Vicksburg, Miss.

Abstract

The risks posed by unknown underground cavities and the difficulty of locating these cavities are emphasized by the variety of techniques under investigation. Every geophysical method, save magnetics, was described by advocates as feasible and appropriate for locating anomalies under certain conditions. The approaches include refraction, reflection, surface wave analysis, and acoustic probing. Additionally, electrical conduction studies are concentrating on the Logn-Bristow-Bates array. Gravity (micro) surveys are receiving strongest usage in Europe, demonstrating a degree of precision unreached in this country. Electromagnetic probing methods both in the form of radar and subsurface transmission are relatively new entries in the field of geophysics.

It may never come to pass that we will ever "see" through the solid earth in the sense of perceiving the real-time integrated image, but the tantalizing hints of that remote possibility show themselves in the future development of two-dimensional acoustic wave systems and radar apparatus. All the imagery and interferometry applications available for use above the earth's surface may become the subsurface explorer's tools.

Parallel to the developing usage of whole wave fronts in space we see more complete usage of the entire wave trains in the temporal domain. Sophisticated electronic circuitry and computers are now and will be in the future letting us squeeze information from all the wiggles instead of just the first few. Investigators are allowed now, by means of their computational equipment, to more closely approach the ideal of the "clean" sciences in that they are numerically modeling newly developed seismic and electromagnetic techniques before trying them on the ground.

Of particular interest was the discovery that microgravity development has been strongly emphasized in Europe much as seismic techniques have in the USA and with at least as much success. The opportunity for a mutual exchange of expertise is obvious.

The last point leads to a general observation on the whole detection method presentation. That observation reiterates the old geophysical truism that no single method works in all geologic environments or for all targets of interest. Cavities can be in wet ground or dry. They can be in high contrast or low contrast to the ground mass when viewed by gravimeters, electric fields, seismic impulses, or electromagnetic waves. The single most important conclusion of these presentations is that the findings of an integrated set of geophysical methods

will be a greater totality than can ever be achieved by the mere sum of individual surveys.

As a final thought we see that for the past 50 years geophysicists have been proving they can find something underground. We have been reminded by this meeting that it is a much different and more complex task to find the absence of something--cavities.

PART IV: SUMMARY AND A LOOK TO FUTURE NEEDS

Those who came to the Symposium expecting to find a "little black box" to take back with them to magically find all subsurface cavities were probably disappointed. However, those who came to gain knowledge of the state-of-the-art in geophysical cavity detection methods probably were well-satisfied with the proceedings of the Symposium, as it accomplished that quite well. Standard geophysical techniques have not been and are not expected to be very successful for the general problem of the detection of subsurface cavities. Current work under way using high-resolution methods and new techniques, however, looks promising. A pressing need now is to educate the user regarding the new techniques and high resolution methods so that adequate field trials can be performed. Response following the Symposium already has indicated a greater willingness to give the new techniques a chance.

High resolution seismic reflection and examinations of surface wave distortions were seismic methods which show promise as cavity detection techniques. There is need for elaborate data processing of high resolution seismic data. Computer modeling of basic seismic wave-cavity interaction mechanisms is invaluable as a tool for interpreting seismic records in the search for cavities in the field. Use of the Meissner "wave front" technique has been used with varying degrees of success in the past; in view of fundamental considerations discussed during the Symposium, the usefulness of the method itself for locating small, localized subsurface features and of interpretation techniques used in the past seem questionable.

The Meissner technique warrants thorough examination with regard to fundamental principles, field procedures, and interpretation methods. Also, the crosshole seismic method needs thorough field trials to demonstrate its possibilities and limitations for delineating localized features. Another technique which warrants investigation for cavity detection is a refined seismic fan shooting approach.

Electromagnetic geophysical methods were not too familiar to the majority of the Symposium attendees. However, electromagnetic methods have been used for subsurface probing since the early 1900's. Subsurface probing radar has been used successful to map fractures, cavities, layers, and other features. Like the other geophysical methods, radar has limitations. Primarily the major limitation is range, which many times can not be predicted in advance of field trials. Subsurface moisture is a major factor in limiting penetration range. For case where penetration is sufficient, delineation of small, localized features can be excellent. Much work is envisioned and planned for the improvement of geologic radars and in the data processing and interpretation of radar dara. Crosshole electromagnetic methods have also been used with some success; computer modeling has been very valuable in predicting patterns to be expected in the field.

One of the real surprises of the Symposium was the discussions regarding the prominence and success of microgravimetry as a cavity detection method in Europe. In fact, gravity methods seem to enjoy a status at least equal to other geophysical methods for site investigations in Europe. The real impetus to gravity microgravity meters in the mid-1960's. The method can be used virtually anywhere, even in busy urban

areas, and has application for mapping of bedrock, groundwater, fractured rock, cavities, etc. A real effort needs to be made to utilize these methods on site investigations in this country.

Although resistivity methods were not covered to the extent desirable in the Symposium, they have been used with some success for cavity detection. The variety of electrode arrays give great versatility to the methods. Pole-dipole arrays (Bristow method) give the ability not only to detect but to predict the exact location. Refinements of the field techniques and interpretation methods of pole-dipole methods should be attempted. Standard, constant spacing Wenner profiling has also been successful in some cases. A constant spacing resistivity survey in a grid pattern followed by contouring should be investigated.

It is important to realize that a single geophysical method can not be used for all sites with guaranteed success. A suite of techniques should be planned which are designed for a specific site. The geophysicist should be brought into the investigation early in the process, should be given all available information regarding the site of interest, and should work closely with project geologists and engineers. The following sections list ongoing research accomplishments, recommendations of future needs in geophysical research, and recommendations of future needs in improved geophysical site investigation and selection procedures which were discussed on the final day of the Symposium.

ONGOING GEOPHYSICS RESEARCH ACCOMPLISHMENTS

ACOUSTICAL

1. LAND AND WATER SONAR

   A) IMPROVED INSTRUMENTATION

   B) IMPROVED DATA PROCESSING

ELECTRICAL

1. SURFACE AND BOREHOLE RESISTIVITY

   A) IMPROVED TECHNIQUES AND INSTRUMENTS

   B) IMPROVED DATA INTERPRETATION

ELECTROMAGNETIC

1. *RADAR*

   A) INVESTIGATION OF NEW APPLICATIONS

NUCLEAR

A) IMPROVED INSTRUMENTS AND INTERPRETATION PROCEDURES

MICRO GRAVITY

A) IMPROVED INSTRUMENTS AND INTERPRETATION PROCEDURES

INVENTORY

A) MAPPING OF ROCKS SUBJECT TO CAVITIES

ONGOING GEOPHYSICS RESEARCH ACCOMPLISHMENTS (Continued)

SEISMIC

1. REFRACTION

    A) IMPROVED INSTRUMENTATION

    B) IMPROVED RESOLUTION

    C) AUTOMATED (COMPUTER) INTERPRETATION PROCEDURES

2. REFLECTION

    A) IMPROVED INSTRUMENTATION (SIGNAL STACKING, ETC.)

    B) IMPROVED "SHALLOW" DATA PROCESSING

3. CROSSHOLE

    A) DEVELOPMENT OF REPEATABLE VER. & HOR. POLARIZED S-WAVE SOURCE

    B) COMPUTER APPLICATIONS OF SNELL'S LAW

    C) BETTER TEST PROCEDURES

    D) MORE CONSISTENT TEST RESULTS

4. UPHOLE/DOWNHOLE

    A) DEVELOPMENT OF HOR. POLARIZED S-WAVE SOURCES

    B) AUTOMATED (COMPUTER) INTERPRETATION PROCEDURES

5. WAVEFRONT

    A) SYNTHETIC RAYPATH CONSTRUCTION

    B) AUTOMATED (COMPUTER) INTERPRETATION PROCEDURES

6. RAYLEIGH WAVE

    A) DEVELOPMENT OF HIGH FORCE LEVEL PROGRAMMABLE VIBRATORS

FUTURE NEEDS IN GEOPHYSICAL RESEARCH

ANALYTICAL

1. ESTABLISH LIMITATIONS OF ALL GEOPHYSICAL METHODS
2. DEVELOP COMPUTER PROCEDURES FOR AMALGAMATION OF DATA OBTAINED BY THE "SUITE" APPROACH
3. PERFORM COMPUTER MODEL STUDIES TO:

   A) VERIFY UNIQUENESS OF INTERPRETATION

   B) DICTATE SENSOR PLACEMENT FOR IN SITU MEASUREMENTS
4. ESTABLISH WORKING RELATIONSHIP WITH OIL COMPANIES IN AN EFFORT TO APPLY EXISTING TECHNOLOGY TO SHALLOW ZONES OF ENGINEERING INTEREST
5. RELATE AS MANY MEASURABLE PARAMETERS AS POSSIBLE TO ENGINEERING PROPERTIES
6. ANALYZE ENTIRE SEISMIC WAVE SIGNATURES AS OPPOSED TO FIRST ARRIVALS

FIELD METHODS

1. PREPARE FOR TRANSITION TO DIGITAL DATA ACQUISITION
2. DEVELOP REPEATABLE (PREFERABLY NONDESTRUCTIVE) P AND S-WAVE SEISMIC SOURCES
3. STUDY MECHANICAL IMPEDANCE OR STIFFNESS OF SOILS BY SURFACE AND CROSSHOLE VIBRATORY TECHNIQUES
4. STUDY INTERNAL AND EXTERNAL ACOUSTIC RESONANCE CAVITY EXCITATION FOR LOCATION AND DELINEATION
5. MAINTAIN AN OPEN MIND WITH RAGARD TO APPLICATIONS OF "NEW" GEOPHYSICAL TECHNIQUES (MICROGRAVITY, MAGNETICS, AND RADAR)
6. STUDY MECHANICS OF PIPING AND SINKHOLE COLLAPSE
7. INVESTIGATE (OR PERFECT) RESISTIVITY METHODS

   A) SINGLE POINT, HIGH ENERGY INPULSE

   B) CROSSHOLE FOCUSED CURRENT
8. REMEDIAL MEASURES OR STABILITY CONCERNED WITH SINKHOLES

FUTURE NEEDS FOR IMPROVED GEOPHYSICAL SITE INVESTIGATION AND SELECTION PROCEDURES

1. RECOGNIZE THAT A LARGER PERCENTAGE OF TOTAL PROJECT COST DEVOTED TO SITE INVESTIGATION AND SELECTION (REMOTE SENSING, GEOLOGY, GEOPHYSICS) INITIALLY CAN HELP PREVENT CASES WHERE SUBSEQUENT REMEDIAL ACTIONS FOR FOUNDATIONS OF COMPLETED STRUCTURES EXCEEDS THE TOTAL INITIAL PROJECT COST

2. RECOGNIZE THAT GEOPHYSICS OFFERS VALUABLE, PRACTICAL, AND COST EFFECTIVE RECONNAISSANCE AND DETAILING POSSIBILITIES IN SITE INVESTIGATIONS

3. BRING GEOPHYSICS AND GEOPHYSICISTS "INTO THE PICTURE" EARLY IN THE SITE SELECTION PROCESS

4. GIVE THE GEOPHYSICIST ALL THE INFORMATION AVAILABLE REGARDING THE SITES OF INTEREST

5. PROMOTE THE CONCEPT OF INTERPLAY, COORDINATION AND COOPERATION BETWEEN GEOPHYSICIST, GEOLOGIST, AND DESIGN ENGINEER TO ACHIEVE THE UTMOST IN ACCURATE SITE ANALYSIS

6. RECOGNIZE THAT GEOPHYSICAL DATA ACQUISITION AND INTERPRETATION ARE COMPLEX - ONLY AGENCIES OR FIRMS OF DEMONSTRATED CAPABILITY SHOULD BE USED

7. RECOGNIZE THAT A SUITE OF GEOPHYSICAL METHODS IS PREFERABLE AND USUALLY NECESSARY TO GIVE THE GREATEST ASSURANCE OF SUCCESS OF CAVITY DETECTION AND RESOLUTION OF OTHER SUBSURFACE DETAIL

8. REALIZE THAT IN SOME CASES CAVITIES ARE SO SMALL AND NUMEROUS OR THE GENERAL CAVITY SYSTEM IS SO COMPLEX THAT DETECTION OF INDIVIDUAL CAVITIES IS NOT ONLY IMPRACTICAL BUT NOT THE BEST PROCEDURE. INSTEAD, A ZONING APPROACH TO SUBSURFACE EVALUATION IS PREFERABLE FOR THESE CASES

APPENDIX A

AGENDA OF THE SYMPOSIUM ON DETECTION OF SUBSURFACE CAVITIES

Monday, July 11

Get Acquainted Reception

Tuesday, July 12

Registration

Announcements, organization

Welcome to Vicksburg--COL John L. Cannon, Commander and Director, Waterways Experiment Station

Welcome from OCE. Statement of Corps Interest and Needs in Cavity Detection--Paul Fisher, Office, Chief of Engineers

Break

KEYNOTE ADDRESS--Engineering Implications of Karst or Get the Karst before the Horst--William E. Davies, U. S. Geological Survey

Lunch

Show-n-Tell Examples of the Use of a Borehole TV System--Fred Smith, Waterways Experiment Station

Case History, Garthright Dam--John L. Bowman, Middle East Division, U. S. Army Corps of Engineers

Break

Case History of Meramec Park Lake Cavity Detection--Gregory Hempen, St. Louis District, U. S. Army Corps of Engineers

Case Histories, Problems of Buried Karst and Caverns, Florida and Puerto Rico--Fred Dreves, Jacksonville District, U. S. Army Corps of Engineers

Foundation Investigation, Letterkenny Army Depot--William Baldwin, Baltimore District, U. S. Army Corps of Engineers

Dinner

Wednesday, July 13

Case History, Radford Army Ammunition Depot--Carl S. Anderson, Norfolk District, U. S. Army Corps of Engineers

Tunnel Detection Problems in Viet Nam--E. E. Addor, Waterways Experiment Station

TVA Philosophy and Methodology for Site Investigation--Richard Hopkins Tennessee Valley Authority

Geophysics Versus the Cavity Detection Problem--D. K. Butler, Waterways Experiment Station

Break

Overview of Cavity Detection Methods--Richard Benson, Technos, Inc.

High Resolution Seismic Reflection Measurements for Cavity Detection--Dr. T. E. Owens, Southwest Research Institute

Lunch

Development of a Pulse Echo Technique for Void Detection in Concrete Structures--A.M. Alexander, Waterways Experiment Station

Effects of Subsurface Cavities on Wavefront Diagrams--A. G. Franklin, Waterways Experiment Station

Field Evaluation of Surface Wave Distortions over Near Surface Cavities and Comparison of the Results with Finite Difference Computer Models--Dr. Richard Rechtien, University of Missouri at Rolla

Subsurface Cavity Detection Using Acoustic Holography and Related Techniques--Gerald L. Fitzpatrick, Holosonics, Inc.

Historical-Geological Tour of the Vicksburg National Battlefield--Dr. Charles Kolb, Consultant

Poolside Cookout

<u>Thursday, July 14</u>

WES Geophysical Capabilities and Cavity Detection Program--R. F. Ballard, Jr., Waterways Experiment Station

Overview of Electromagnetic Methods in Geophysics and Application of Radar to the Detection of Cavities in Salt--Dr. Robert R. Unterberger, Texas A&M University

Break

Detection of Subsurface Cavities Using Impulse Radar--Joseph V. Rosetta, Jr., Geophysical Survey Systems, Inc.

Electro-Magnetic Cross-Borehole Probing for the Detection of Anomalies--
Darrel Lager, Lawrence Livermore Laboratory

Lunch

Tour of the Waterways Experiment Station

Detection of Subsurface Cavities by Surface Remote Sensing Techniques--
L. S. Fountain, Southwest Research Institute

Microgravity Method Applied to the Detection of Cavities--Robert Neumann,
Compagnie Generale de Geophysique

Moonlight Boat Cruise on the Mississippi

Friday, July 15

Review of Detection Methods Presentations--James B. Warriner, Waterways
Experiment Station

Round Table Discussion: Moderator--James W. Erwin, South Atlantic Division,
U. S. Army Corps of Engineers

Open Discussion Session

A Look to Future Needs in Geophysical Research and Development for the
Detection of Subsurface Cavities--Robert F. Ballard,
Waterways Experiment Station

Adjourn

List of Exhibitors

Bison Instruments, Inc., Minneapolis, Minnesota--Steve Haverberg, Applications Engineer

Geophysical Survey Systems, Inc., Hudson, New Hampshire--Joseph Rosetta,
Vice President

Nimbus Instruments, West Sacramento, California--Doug Acrice, President

SIE, Houston, Texas--Bobby Parr, Senior Sales Engineer

APPENDIX B: LIST OF ATTENDEES

Symposium on Detection of Subsurface Cavities

12-15 July 1977

Vicksburg, Mississippi

EUGENE E. ADDOR, Botanist
USAE Waterways Experiment Station
P. O. Box 631
Vicksburg, MS 39180
601/636-3111, ext. 2516 (FTS 542-2516)

CARL S. ANDERSON, JR., Chief, Geotechnical Engr Section, Design Branch
U. S. Army Engineer District, Norfolk
803 Front Street
Norfolk, VA 23510
804/446-3664 (FTS 924-3664)

JOHN N. BAEHR, Geologist
U. S. Army Engineer District, Mobile
P. O. Box 2288
Mobile, AL 36628
690-2680

WILLIAM J. BALDWIN, JR., Engineering Geologist
U. S. Army Engineer District, Baltimore
P. O. Box 1715
Baltimore, MD 21103
301/962-4451 (FTS 922-4451)

ROBERT F. BALLARD, JR., Chief, Geodynamics Branch
USAE Waterways Experiment Station
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USAE Waterways Experiment Station
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601/636-3111, ext. 2630 (FTS 542-2630)

RICHARD C. BENSON, Chief Geophysicist
Technos Inc.
P. O. Box 330891
Miami, FL 33133
305/858-4665

AARON L. BOGGS, Civil Engineer
U. S. Army Engineer District, Vicksburg
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601/636-1311, ext. 214

JOHN C. BOWMAN, JR., Geologist
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703/667-2295 (FTS 652-2358 or 652-2352)

ROBERT C. BOYCE
Soil Conservation Service, USDA
269 Federal Center Building
Hyattsville, MD 20782
FTS 436-8655

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